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MAGNETIC CONTROL
of
INDUSTRIAL MOTORS

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the General Electric Advanced
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TO

Marianne Bobby Heumann

PREFACE

From small beginnings, the industrial control industry has grown to respectable size. Behind the motors supplying power for industrial production, stands the control equipment, recognized as an essential partner, directing the performance of the motor and affording protection to the drive and the operator. Within the scope of control are devices, controllers for individual motors, and integrated control systems for whole production lines, involving a multiplicity of rotating and stationary power apparatus.

From an engineering point of view, there are two major aspects of control, design and application. Whereas the designer concentrates on a device or a circuit or a mechanical arrangement of parts, the application engineer must have a knowledge of what control equipments can accomplish and what the requirements of a particular drive system are, and what performance can be expected of various types of motors.

This is intended to be an application book. Its aim is to explain performance of motors, characteristics of control devices, and the function of commonly used control circuits. Complete controllers of various frequently used designs are discussed. Emphasis is placed on consideration governing the selection of controllers to perform specific jobs.

Chapters 2, 3, and 13 of the book cover in more detail the subject matter that I have presented in the serial "Basic Procedures in Motor Control," which is currently appearing in the *General Electric Review*. The first installment was in the May, 1947, issue of that magazine.

Perhaps more than any other engineering activity, control engineering depends for its success on teamwork. A great deal of specialized knowledge of mechanical and electrical phenomena enters into the design of many a control equipment. I acknowledge gratefully that much of the information contained in this book is based on work done by my associates in the General Electric Company. I wish also to express my appreciation to other manufacturers who placed material at my disposal.

GERHART W. HEUMANN

SCHENECTADY, NEW YORK
May, 1947

CONTENTS

INTRODUCTION 1

CHAPTER 1 SYMBOLS AND DIAGRAMS 5

CHAPTER 2 PRINCIPLES OF DIRECT-CURRENT MOTOR OPERATION 20

CHAPTER 3 PRINCIPLES OF ALTERNATING-CURRENT MOTOR OPERATION 87

CHAPTER 4 DIRECT-CURRENT CONTACTORS AND RELAYS 145

CHAPTER 5 ALTERNATING-CURRENT CONTACTORS AND RELAYS 170

CHAPTER 6 ACCESSORIES 196

CHAPTER 7 PILOT DEVICES 216

CHAPTER 8 ELECTRONIC DEVICES 240

CHAPTER 9 RESISTORS AND RHEOSTATS 256

CHAPTER 10 CONSTRUCTION OF CONTROL PANELS 283

CHAPTER 11 BASIC DIRECT-CURRENT CONTROL CIRCUITS 322

CHAPTER 12 BASIC ALTERNATING-CURRENT CONTROL CIRCUITS 355

CHAPTER 13 AMPLIDYNE CONTROL CIRCUITS 377

CHAPTER 14 PROTECTION 397

CHAPTER 15 SOLENOIDS, THRUSTORS, BRAKES 419

CHAPTER 16 MANUAL CONTROLLERS 440

CHAPTER 17 GENERAL-PURPOSE CONTROLLERS 451

CHAPTER 18 DIRECT-CURRENT INTERMITTENT-DUTY CONTROLLERS 488

CHAPTER 19 ALTERNATING-CURRENT INTERMITTENT-DUTY CONTROLLERS 537

CHAPTER 20 MAINTENANCE OF CONTROL EQUIPMENT 571

INDEX 585

INTRODUCTION

The engineering of industrial control equipment is both a science and an art. Given the mechanical characteristics of a drive, the performance characteristics of a motor, and the layout of a control equipment, the control engineer is in a position to calculate rigorously the performance which can be expected of the equipment; that is to say, how fast the drive will run, within what time it will accelerate, what torque the motor will develop, how it will decelerate, how the speed will react to torque changes, how accurately speed can be held, etc.

However, it is often impossible to forecast accurately the performance of a drive because of difficulties in obtaining sufficiently correct mechanical data. When there is friction it is nearly impossible to calculate accurately the amount of power taken by a drive. The author recalls an instance where two lift bridge spans were built according to identical specifications and from identical sets of drawings. Both spans were constructed by reliable and responsible contractors who fully met the specifications. Nevertheless, when the two bridges were placed in service, one span took twice as much power as the other one. It becomes then the task of the engineer to use proper judgment, and from his experience and knowledge of the application to design the control equipment so that it possesses sufficient flexibility for adequate performance, even if the mechanical characteristics of the drive vary over a wide range.

Another problem confronting the control engineer is the variety of operating conditions under which the control may have to perform. A shipyard crane handles occasionally a very heavy piece of machinery which taxes the crane to the limit of its stability. Most of the time, however, the crane handles a variety of loads well below its rated capacity. Here again the control engineer is called upon to use judgment in designing a control equipment which, although it may not give the best theoretically possible performance under any one specific condition of load, will nevertheless give the best all-round performance under all possible conditions of loading.

Of greatest importance is the economic factor. Control equipment is designed and built to be sold to a prospective user. Here again, skill and judgment influence the decision of what type of control to apply. The engineer must know what features are absolutely necessary and what features, though desirable, could be dispensed with. Then it becomes a question of whether the cost of the desirable features is economically warranted. It is good judgment to offer a control equipment which, although it may not contain all possible refinements, is low in cost.

The cost of a control equipment is not only the expense required to manufacture it but also the expense incurred in engineering it. Solving each problem, as it comes up, the rigorous scientific way would consume so much time that the control engineer's work would never be done. Thus he looks for methods which enable him to make a quick check of control performance with a degree of accuracy satisfactory for the average practical case, especially in view of the fact that the assumptions on which performance calculations are based are too uncertain to warrant spending the time required for rigorous calculations.

Industrial control comprises equipment used to obtain a specific performance of an industrial equipment, in the majority of cases a motorized drive. The motor provides the force to move the drive, but control determines what the motor is to do. Control equipment is applied at the point of utilization of power. Equipment which governs the distribution of power and the protection of the power supply system belongs in the classification of switchgear, which will not be treated in this book.

There are two major fields covered by control engineering. Included in the first is the design of devices and circuit components out of which control equipments are built. The second is the design of equipments. This latter phase of control engineering requires the study of the application problem involved, the design of the circuits to solve the application problem, the selection of devices necessary to realize the circuits chosen, and finally the physical layout of a controller which contains the devices, properly connected, in a mechanical arrangement suitable for the specific conditions of the application. This phase of control engineering will be treated in this book. Its purpose is to help in understanding the application of control to specific jobs in industry. For quite a number of years the tendency has been in favor of the use of magnetic control, and therefore magnetic control will be considered primarily.

The language in which a control engineer expresses his thoughts and by means of which he discloses the function of a controller consists of symbols and connection diagrams. This book opens with a presentation of symbols and a discussion of wiring diagrams. The next two chapters are devoted to a presentation of the characteristics of d-c and a-c motors most commonly used in industrial installations. They are followed by chapters on control devices, circuit elements, and basic circuits, forming the building blocks out of which control equipment can be constructed.

Amplidynes have gained an important place in control systems for adjustable-voltage drives, and a chapter is devoted to amplidynes and their control circuits. Another chapter deals with electronic devices. It is not the intention of this book to cover the field of purely electronic control, as a separate book would be necessary to cover it adequately. It is rather intended to familiarize the reader with electronic devices commonly used in conjunction with magnetic control.

In the concluding chapters, typical controllers for general purpose applications and selected intermittent-duty controllers are discussed. Controllers are presented which are used widely in industry and illustrate the most important principles of standard control systems. A concluding chapter makes general recommendations for maintenance of control equipment.

Whenever applicable, the "per unit" system is used to represent the performance characteristics of motors or controllers. In this system various quantities are expressed as a ratio to a base quantity, which is taken as unity. Base quantities have to be defined in each case. Usually they are the rated or normal quantities. For instance, rated current of a motor is assumed to be its base current, rated speed its base speed. For a-c motors, it is convenient to assume synchronous speed as base speed. To interpret any per unit curves properly, care must be taken to determine the base quantities that apply.

Representing performance data in terms of per unit has the advantage that such data are generally applicable, regardless of the size or rating of the machine for which they have been computed. To translate per unit data into numerical data applying to a specific machine, it is necessary only to multiply the per unit quantities by the numerical value of the base quantity. It is quite customary in technical literature to express performance data in percentage. Both the per unit system and the percentage system are equivalent. Unity in the per unit system equals 100 per cent in the percentage system. The per unit system is handier for carrying out calculations, as per unit quantities can be introduced directly into formulae, whereas calculations with percentage quantities require divisions by 100 or powers of 100.

Formulae which cannot be used for per unit calculations and only for numerical calculations are followed by the symbol ●. Formulae which are correct only on a per unit basis and cannot be used for numerical calculations are followed by the symbol ■. All other formulae in this book hold true for both per unit and numerical calculations. See pages 24, 30, 56 for examples of each kind of formula.

At the end of each chapter is a bibliography pertaining to the subject matter of the chapter. The items in the bibliography are numbered as a convenience in referring to them in the text. Superior numbers in the text designate corresponding references applying to the subject under discussion. Not all the items in the bibliography are referred to in the text; some are of general interest only.

CHAPTER 1

SYMBOLS AND DIAGRAMS

Much industrial control equipment is built every year for many entirely unrelated users. A controller may contain one or a few devices or it may be composed of hundreds of devices. A certain user may have in his plant controllers built by several manufacturers. The men who use and maintain control equipments may be highly specialized experts in the control field or they may be ordinary operators or electricians.

It is of great importance to have available a method to represent control equipment on drawings which is universally applicable and can be understood by everyone versed in the electrical art, regardless of the manufacture of the equipment. The most important information on a control equipment is the connection diagram. It shows in shorthand the circuits, the control devices, and the interconnections with external apparatus. To make a connection diagram, it is necessary to represent the various control devices by symbols. To make connection diagrams most useful both to manufacturers and to users, it is of utmost importance to use standard symbols which are uniform throughout the electrical industry.

American Standard Symbols

In former days each manufacturer made up his own set of symbols, based largely on the physical appearance of devices. Such symbols looked much like outline sketches with electrical connections superimposed. They were unsatisfactory in the long run for various reasons. From the point of view of the manufacturer, they were cumbersome and difficult to draw. From the point of view of the user, functionally equivalent devices of different manufacturers were shown by entirely different symbols, which proved to be rather confusing to the users' electricians and maintenance men. In recent years great progress has been made toward providing the electrical industry with a set of standardized symbols to be used by everybody. The American Standards Association has issued American Standard Z32.3–1945, entitled "Electric Power and Control Symbols."[1] These symbols have found wide acceptance in industry, and they are used throughout this book.

A good set of symbols should satisfy the following postulates:

1. Symbols must be simple and easy to understand. Not only graduate engineers, but factory wiremen, operators, and electricians must be able to follow them, having once understood the basic symbols.
2. Symbols must be concise. Each symbol must represent one, and only one, circuit element. Otherwise it would be impossible to interpret a wiring diagram without a multitude of explanatory remarks.
3. Symbols must be flexible. Basic symbols should be set up for circuit elements out of which a complete symbol for a specific device can be developed, thus allowing for differences in design details and physical arrangement of different manufacturers' devices.
4. Symbols must be easy to draw. Since each type of controller must have its individual diagram, thousands of wiring diagrams are drawn each year. Eliminating all details which are not absolutely necessary to express the meaning of the symbols saves considerable drafting time in the preparation of connection diagrams.

The symbols used by the power industry, on the one hand, and by the communications industry, on the other, were developed somewhat independently over a period of years. Consequently, several conflicts developed in which the same symbols meant two entirely different circuit components in the two industries. With the growing use of electronic equipment by the power industry, considerable confusion existed, as plant engineers had to get used to different sets of symbols and, when reading a wiring diagram, they had to make certain who had drawn it. To add to the confusion, some diagrams were drawn using symbols from both systems.

Under the pressure brought about by World War II conferences were held under the auspices of the American Standards Association whereby agreement was reached on the use of certain basic symbols to avoid these conflicts. The symbols are shown in Fig. 1. To allow for existing practices in various branches of the electrical industry, alternatives are permitted. This means that a certain circuit element can be represented by one of several symbols, but each symbol can designate only one circuit element. In Fig. 1 the first symbol, where two alternatives are shown, and the first and second symbols, where three choices are given, are the symbols generally used by the power industry. From these basic symbols are built adaptations to designate specific devices or pieces of apparatus.

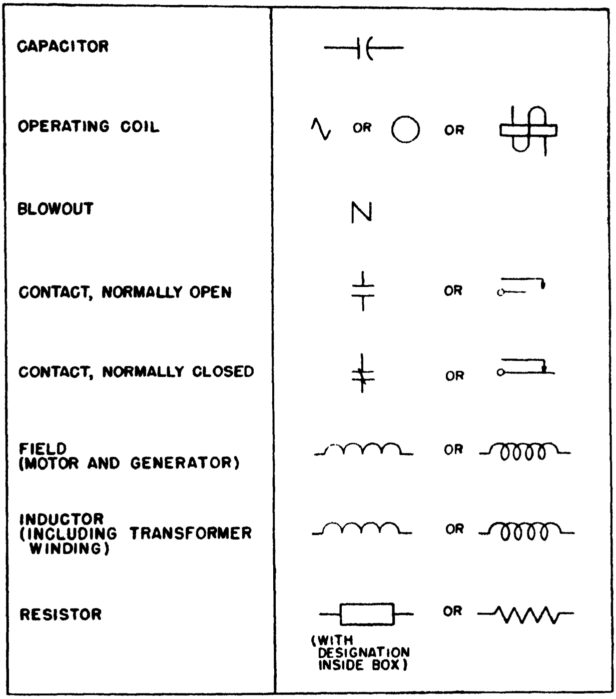


FIG. 1. Basic symbols for electric apparatus.

Figure 2 shows typical component symbols for wiring diagrams in accordance with American Standard Z32.3–1945. How these component symbols can be adapted to make up the complete symbol of a specific device is illustrated in Fig. 3. To the left is a pictorial view of a single-pole d-c contactor with electrical interlock. The back view composite symbol of the contactor is shown to the right, using component symbols from plates *J*, *K*, and *M* of Fig. 2. The main pole, which carries a power circuit, is shown by heavy lines, whereas the coil and interlock, which carry control power only, are shown by light lines. Terminals indicate where power and control connections are made to the contactor.

The component symbols can be adapted equally well to represent more complicated devices. As an example, Fig. 4 shows the symbol for a six-circuit, three-position, reversing cam type master switch. In the pictorial view the cover is omitted so that the contacts, cams, and terminal boards can be seen. Symbol *a* is similar to plate *IIH* in Fig. 2. The contacts are shown in numerical order, together with an indication of master switch positions. The contact closing sequence, as the master switch is moved from point to point, is indicated by *x*'s. The symbol *x* shows on which master switch position each contact is closed. Where no *x* is shown, the contact remains

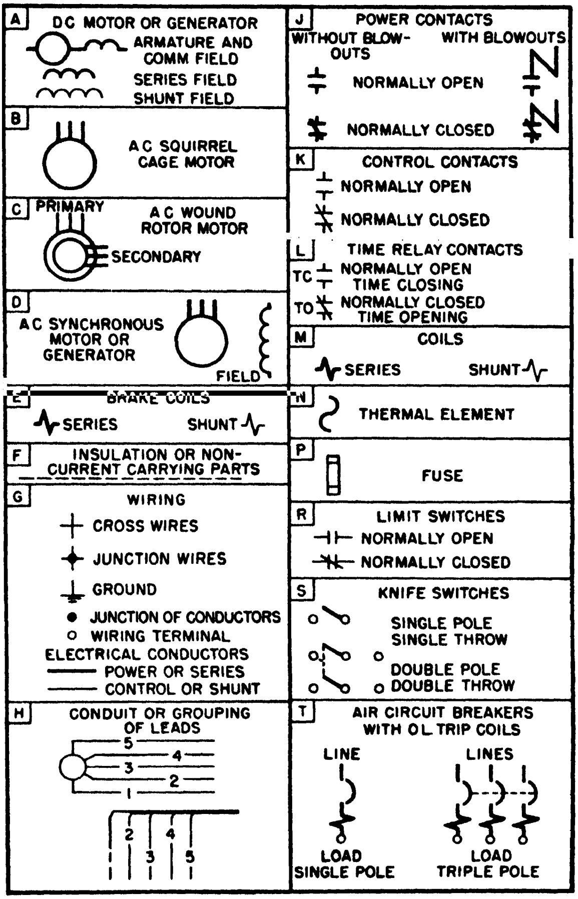


FIG. 2. Typical component symbols for control wiring diagrams.

open. Thus contact $1MS$ is closed in the off position but open in all other positions. Contact $2MS$ is closed in positions 1, 2, 3, both forward and reverse, but open in the off position. Similarly, the closing sequence is given for the other contacts.

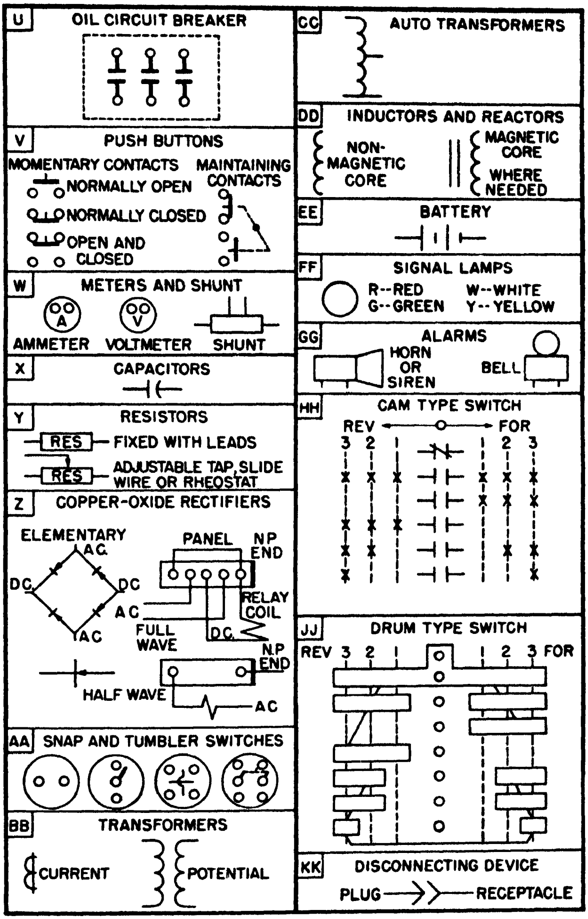
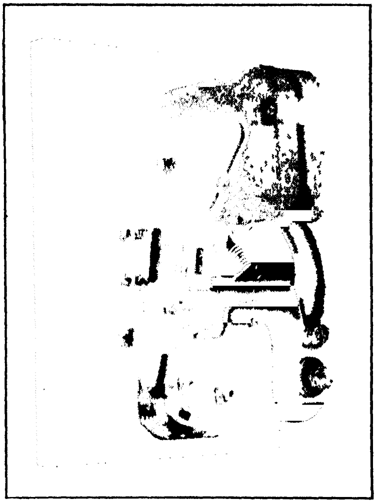


FIG. 2 (*Continued*)

Usually the complete development of the master switch is given only on the elementary diagram or on a sequence diagram. On connection diagrams or on external connection diagrams it is customary to show only the arrangement of the terminal board to which external connections are brought. Symbol *b* in Fig. 4 shows the master switch terminal board with the arrangement of external wiring.



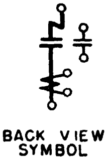


FIG. 3. Single-pole d-c contactor and equivalent composite symbol.

Device Markings

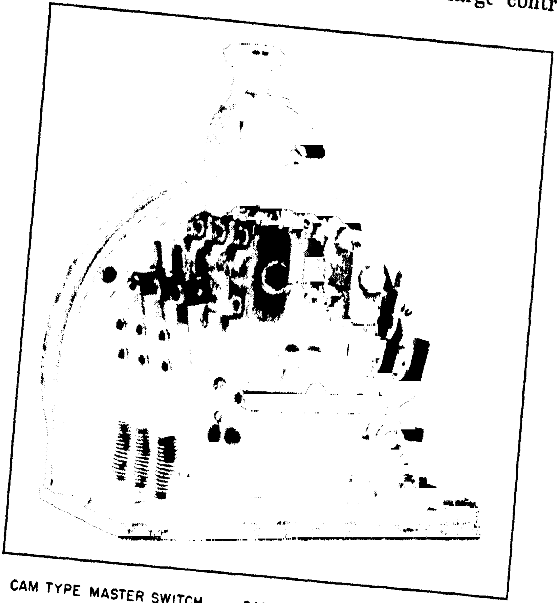
As many controllers comprise a multiplicity of devices, each contactor, relay, and other device is marked by a device designation, indicative of its function. Table 1 lists the most commonly used designations.

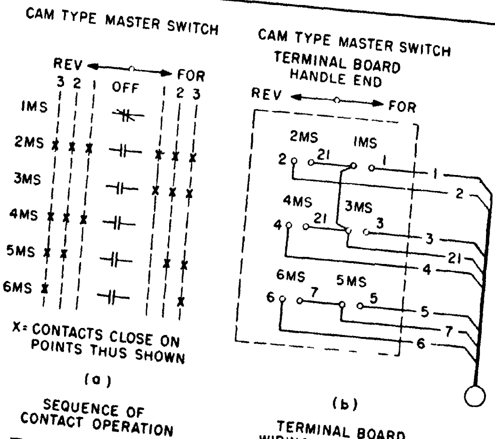
If more than one device of the same function are used, a prefix is added to the device marking. For example, the two forward contactors of a d-c controller are marked 1*F*, 2*F*, and the corresponding reverse contactors are marked 1*R*, 2*R*. Successive accelerating contactors are marked 1*A*, 2*A*, 3*A*, etc.

Terminal Markings

To enable an electrician to connect the equipment at the installation and the maintenance man to identify circuits after the equipment has been installed, it is necessary to mark each terminal on the connection diagram. As far as control circuits are concerned, it is customary to use an arbitrary numbering system. On large control equipments, blocks of numbers or other discriminating designations may be assigned to discriminate among various sections of the control. There are no set rules, and any system is satisfactory as long as it is carried through with consistency. Duplication of numbers, without some definite and easily recognizable discrimination, should be avoided under all circumstances.

Sometimes a multiplicity of standard controllers, which have their terminal markings stamped on, is a part of a large control equipment. This arrangement means that the same standard control terminal markings appear several times on a connection diagram. In such a case it is advisable to assign to each circuit a definite and distinc-





(a)

SEQUENCE OF CONTACT OPERATION

(b)

TERMINAL BOARD WIRING ARRANGEMENT

Fig. 4. Diagram symbol for cam type master switch.

TABLE 1

Device Markings for Wiring Diagrams

Device	Contactor	Relay	Other	Device	Contactor	Relay	Other
Accelerating	*A*	*AR*		Main breaker			*MB*
Ammeter switch			*AS*	Master switch			*MS*
Armature shunt	*AS*			Maximum torque		*MTR*	
Auto-transformer			*AT*	Motor circuit switch			*MCS*
				Motor field			*MF*
Brake	*B*	*BR*					
Capacitor			*C*	Open phase and phase reversal		*OPR*	
Circuit breaker			*CB*	Overload		*OL*	
Closing coil		*CCR*	*CC*	Overspeed		*OSR*	
Control		*CR*		Overspeed switch			*OSS*
Control switch			*CS*				
Counter emf		*CEMF*		Plugging	*P*	*PR*	
Current limit		*CLR*		Plugging forward		*PF*	
Current test block			*CTB*	Plugging reverse		*PR*	
Current transformer			*CT*	Potential interlocking		*PIR*	
				Potential test block			*PTB*
Down	*D*			Potential transformer			*PT*
Dynamic braking	*DB*	*DBR*		Power factor		*PFR*	
				Power factor meter			*PF*
Emergency switch			*ES*	Pressure governor			*PG*
Exciter field	*EF*	*EFR*		Push button			*PB*
Field	*F*	*FR*		Rectifier			*REC*
Field accelerating	*FA*	*FAR*		Relay test block			*RTB*
Field discharge	*FD*	*FDR*		Resistor			*RES*
Field economy	*FE*	*FER*		Reverse, run, raise	*R*		
Field loss (failure)	*FL*	*FLR*					
Field weakening	*FW*	*FWR*		Sequence protective		*SPR*	
Float, flow switch			*FSW*	Slow-down		*SR*	
Forward	*F*	*FR*		Squirrel cage protective		*SCR*	
Full field	*FF*	*FFR*		Start	*S*		
Fuse			*FU*	Switch			*SW*
Ground detector			*GD*	Time closing			*TC*
				Time opening			*TO*
High speed	*HS*	*HSR*		Time relay		*TR*	
Hoist	*H*	*HR*		Time switch			*TS*
				Transfer relay		*TRR*	
Jam, jog	*J*	*JR*		Trip coil			*TC*
Kick off	*KO*	*KOR*		Undervoltage	*UV*	*UVR*	
				Unloader coil			*UC*
Limit switch			*LS*	Up	*U*		
Line contactor	*M*	*MR*					
Low speed	*LS*	*LSR*		Voltage regulator		*VRG*	
Lowering	*L*	*LR*		Voltmeter switch			*VS*

tive number, which is carried through the diagram, and to show the terminal markings, which are actually stamped on a standard device, in brackets.

Concerning power terminal markings on electrical apparatus, American Standard C6.1–1944[2] has been sponsored by the National Electrical Manufacturers Association (NEMA), and these standard terminal markings should be used on all controller diagrams. The markings consist of a letter followed by a suffix. Table 2 gives most frequently used markings.

TABLE 2

TERMINAL MARKINGS USED ON WIRING DIAGRAMS

	D-C	*A-C*
Brake	*B*1, *B*2, *B*3, etc.	*B*1, *B*2, *B*3, etc.
Brush on commutator (armature)	*A*1, *A*2	*A*1, *A*2, *A*3, etc.
Brush on slip ring (rotor)		*M*1, *M*2, *M*3, etc.
Field (series)	*S*1, *S*2	
Field (shunt)	*F*1, *F*2	*F*1, *F*2
Line	*L*1, *L*2	*L*1, *L*2, *L*3, etc.
Resistance (armature)	*R*1, *R*2, *R*3, etc.	*R*1, *R*2, *R*3, etc.
Resistance (shunt field)	*V*1, *V*2, *V*3, etc.	
Stator		*T*1, *T*2, *T*3, etc.
Transformers (high-voltage)		*H*1, *H*2, *H*3, etc.
Transformer (low-voltage)		*X*1, *X*2, *X*3, etc.
Transformer (tertiary winding)		*Y*1, *Y*2, *Y*3, etc.

As a general rule, letters preceded by figures represent device designations. Letters followed by figures are terminal markings.

Purpose of Wiring Diagrams

Wiring diagrams are prepared by engineers for four purposes. Depending on the various uses made of the diagram, certain features are of preponderant importance, and a complete diagram or set of diagrams must include all these features.

1. *Wiring diagrams serve as a record for the engineers,* both in the manufacturer's and in the user's organization. Engineers are primarily interested in elementary diagrams setting forth the circuits employed and clearly explaining the function of the controllers. For this purpose the diagrams must be so clear and concise that any trained engineer who may not have been connected with the design or the initial installation of the controllers can fully understand their function.

2. *Wiring diagrams are used by the factory wiremen* to wire up parts of control equipments such as panels. The wiremen do not

need to understand the function of the controllers. However, they must know exactly how power and control wires are to be run between terminals of devices. To them the wiring diagram must show every device on the panel in its proper physical relation to other devices and the connections between the terminals of these devices.

3. *Wiring diagrams are used by the installing electricians* to interconnect the various pieces of equipment comprising a complete control installation. They are not interested in the operation or the internal panel wiring. They must know, however, the arrangement of outgoing power and control terminals on each piece of equipment and the external connections to be made between them.

4. *Wiring diagrams are used by operators and maintenance men* to supervise the equipment and to "shoot trouble." These men are interested in the function of the equipment, the internal circuits, and the external interconnecting circuits.

For each control equipment, one diagram or a set of diagrams should be made up showing elementary, internal, and external connections.

Elementary Diagrams

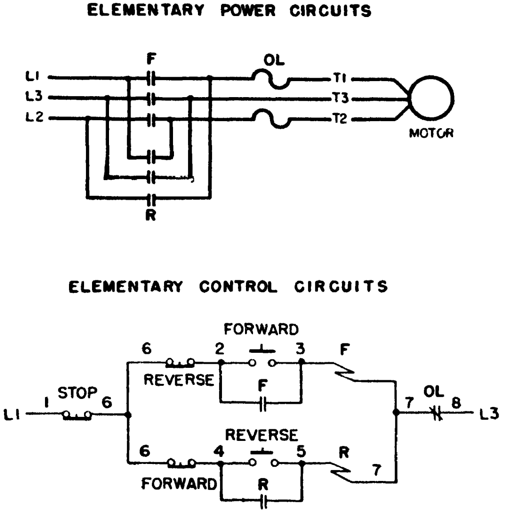
NEMA defines an elementary diagram as follows: [3] "An elementary controller wiring diagram is a diagram using symbols and a plan of connections to illustrate, in simple form, the scheme of control."

This brief definition may be amplified to state that an elementary diagram shows all circuits and device elements of an equipment and its associated apparatus, or any clearly defined portion thereof. Such a diagram emphasizes the device element of a circuit as distinguished from the physical arrangement of the conductors, devices, or device elements of a circuit system.

To emphasize the device elements and show their functional relationships and sequence, physical relationships of devices and device elements are usually disregarded. Circuits are usually drawn in the most direct possible line between and perpendicular to parallel lines representing opposite polarities of voltage sources. Circuits which function inherently in a definite sequence are arranged to indicate that sequence. Elementary diagrams are useful where electrical relationships of circuits and device elements are the principal considerations.

As an example, Fig. 5 shows the elementary diagram of an a-c full-voltage reversing controller. This controller consists of a control panel and push button station. The panel contains two contactors and an overload relay. Power and control circuits are shown separately. Various elements of a device, such as coil, main power contacts, and interlocks of a contactor, are shown in their proper functional position in the circuit, regardless of their physical relationship. Each element of a device carries the marking of the device.

The elementary diagram should show each terminal marking used, both for power and for control. It should also contain a tabulation



NOMENCLATURE

F---- FORWARD CONTACTOR } MECHANICALLY
R---- REVERSE CONTACTOR } INTERLOCKED
OL--- OVERLOAD RELAY (HAND RESET)

FIG. 5. Elementary diagram for a-c magnetic reversing controller.

of device nomenclature. If relays are used, the setting of which can be adjusted, a relay setting table should be given. If the controller contains several hand or automatically controlled positions, a control sequence table should tabulate the connections for each successive position of the controller. It may, for instance, be a master switch or limit switch contact closing table.

Connection Diagrams

Connection diagrams show the connections of an installation or its component devices and equipment. They may show the general physical arrangement of devices, device elements, and also accessory items such as terminal blocks, fuse blocks, and resistors. They may cover internal or external connections or both and contain such detail as needed to make or trace the connections involved.

For this purpose, NEMA Industrial Control Standards use the term *wiring diagram,* which is defined as follows: "A controller wiring diagram is a diagram showing the electrical connections between the parts comprising the controller, and indicating the external connections."

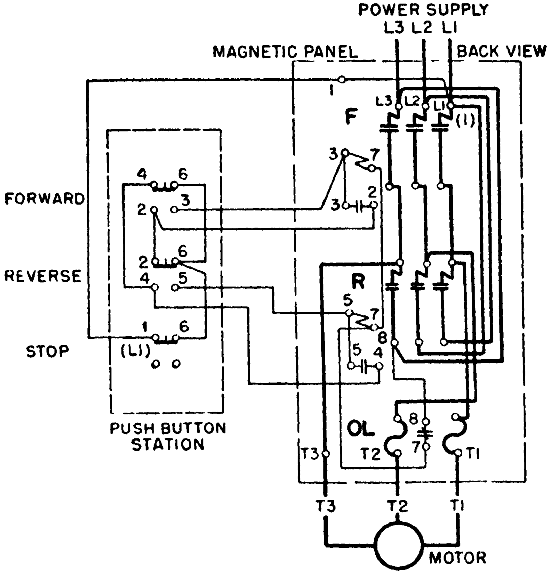


FIG. 6. Connection diagram for a-c magnetic reversing controller.

Figure 6 is the *connection* or *wiring diagram* of the controller shown in Fig. 5. The connections of the control panel are shown in detail, with the complete symbol for each panel device. The various devices are drawn in the same relative location in which they are mounted on the panel. As the wiring is physically in the back of the panel, the panel connections are shown back view, as the wireman would see them when working on the panel.

All devices which are physically part of the panel are shown inside the broken line delineating the panel. The push button station and the motor are not part of the panel, and they are shown outside the broken line. All terminals for outgoing connections are marked.

For a comparatively small controller, the connection diagram as shown in Fig. 6 would suffice to show external connections. However, on large equipments involving a multiplicity of panels and associated external devices, it is advantageous to omit interconnections between panel and other equipment from the connection diagram and to show panel wiring only, in order to keep the diagram at a reasonable size. In such a case an external connection diagram is made up which is sometimes called an interconnection or consolidated diagram. The NEMA definition is as follows:[3] "An external controller wiring diagram is a diagram showing the electrical connections between the controller terminals and outside points, such as connections from the line, to the motor, and to auxiliary devices."

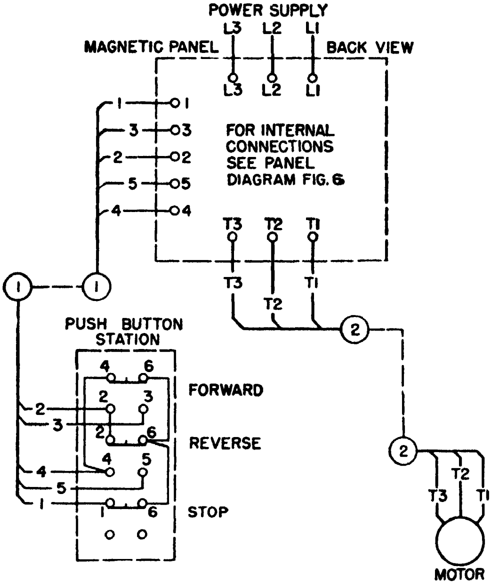


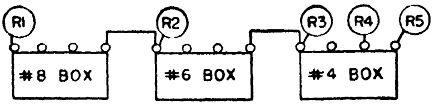
Fig. 7. Typical external connection diagram.

Figure 7 is the external connection diagram of the controller shown in Fig. 6. The internal connections of the panel are omitted and outgoing terminals only are shown. External connections are carried to circles or "rat holes," and like-numbered circles are connected together. When large external connection diagrams are made, involving a large number of interconnections, a tabulation of rat holes should be included to help in locating interconnections on the drawing.

If elementary diagrams and internal and external connection diagrams are made up as separate drawings, it is very essential to place cross references on each drawing.

Construction Diagram

For certain types of equipment a construction diagram is prepared, which NEMA defines as follows: [3] "A controller construction diagram



APPROXIMATE RESISTANCE PER DIVISION

R1-R2 = 1.44 OHMS
R2-R3 = 1.08 OHMS
R3-R4 = 0.48 OHM
R4-R5 = 0.24 OHM
TOTAL = 3.24 OHMS

LIST OF MATERIAL

1-CR9143 UNIT BOX CAT 1928116 G4 (#4 BOX)
1-CR9143 UNIT BOX CAT 1928116 G6 (#6 BOX)
1-CR9143 UNIT BOX CAT 1928116 G8 (#8 BOX)
3 BOXES TOTAL FOR CONNECTIONS BY CUSTOMER PER SKETCH ON THIS PRINT AND WIRING DIAGRAM FURNISHED WITH PANEL

CLASS = 3.24 - 65 - 85 - 230 VOLTS D.C.

INSTRUCTIONS GEH 92

OUTLINE = EACH BOX GEM 15 FIG 1

TYPE CAST GRID RESISTOR FOR 33 HP
SERIES WOUND 230 VOLT D.C. MOTOR

FIG. 8. Typical resistor construction diagram.

is a diagram indicating the physical arrangement of parts such as wiring, busses, resistor units, etc."

The purpose of construction diagrams is to show features of construction specifications in simplified form. They are seldom made up for control panels, as connection diagrams are mostly adequate to show all necessary details for manufacturing panels. Construction diagrams are useful to show the stacking of resistor grids, rectifier disks, etc.

Figure 8 is a typical resistor construction diagram. It contains a sketch showing arrangement of the resistor boxes with location of terminals on each box. Interconnections between boxes are indicated. A tabulation gives the ohmic value of resistance of each division. A list of material, giving the ordering information for the resistor boxes, is included.

BIBLIOGRAPHY

1. American Standards Association, "Electric Power and Control Symbols, Z32.3–1945.
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CHAPTER 2

PRINCIPLES OF DIRECT-CURRENT MOTOR OPERATION

Hardly ever will a control engineer be called upon to design an electric motor. To apply control to a motor, he does not have to lay out its windings, calculate its flux, determine its physical dimensions, etc. However, to coordinate a motor and its control to best advantage, the control engineer has to know how a given motor works and how its characteristics can be influenced by the control to obtain a desired performance. Chapters 2 and 3, therefore, are devoted to a brief discussion of the most commonly used types of d-c and a-c motors, how they work, and what they can do.

Speed-Torque Curves [1, 2]

Motor performance can be most easily visualized by plotting speed versus torque. To apply a motor to a piece of machinery, it is necessary to know the torque the motor is required to deliver at its shaft and the speed at which the machine must run to obtain the desired output of work. Usually the application engineer gathers the necessary data on the machine, selects the size and type of motor to be used, and establishes the desired performance characteristics. It then becomes the problem of the control engineer to select equipment and design circuits by which motor performance is matched to the requirements of the drive and by which proper protection for abnormal conditions is given.

Motors are rated in terms of horsepower and speed. From these data the full-load torque can be determined as follows:

$$\text{Torque in lb-ft} = \frac{\text{rated hp} \times 5252}{\text{full-load rpm}}$$

To compare the performance of various types and sizes of motors and to apply results calculated for one motor to other motors of similar characteristics, it is convenient to express speed and torque in per unit. If rated full load and speed are called base quantities or unity, motor performance at partial loads and at partial speeds can be expressed in terms of per unit of rated full-load values.

When motor speed is plotted versus motor torque, the performance of the drive under varying loads can be visualized. It is also possible to predict how changes in the motor circuit, as obtained by the controller, will affect machine performance. Conversely, if it is known what performance is desired of the machine, a study of the speed-torque curves will aid in the selection of a suitable control circuit.

In plotting speed versus torque, let the horizontal axis or abscissa be torque and the vertical axis or ordinate be speed. These two coordinates determine four quadrants in which speed and torque may be positive or negative. These quadrants represent all possible operating conditions of the motor, as illustrated in Fig. 9.

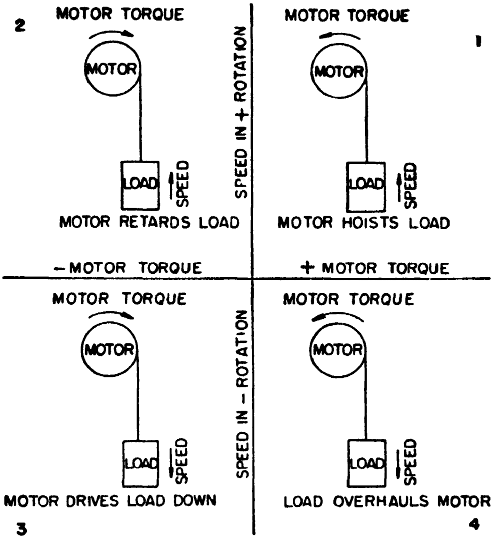


FIG. 9. The four quadrants of motor performance.

In the upper right-hand quadrant 1, both motor torque and speed are positive. In a motor driving a hoist, as an example, this quadrant represents the condition that the motor hoists a load. Motor torque overcomes gravity. The motor delivers power to the load. An equivalent condition exists when the motor drives a friction or inertia load, or a combination of both, in a given direction, which is arbitrarily called positive.

The upper left-hand quadrant 2 covers the operating condition where speed is still positive but torque is negative. This means that the motor develops a torque which is opposed to the load torque and retards the load. In other words, the motor develops a braking torque. This condition is of no practical significance in a hoist drive. However, if a motor drives an inertia load to which it is geared solidly, quadrant 2 covers the condition where the motor develops a torque opposing the load torque due to the kinetic energy of the inertia load. The motor absorbs energy from the load, which is either dissipated as ohmic loss or fed back to the power supply.

In lower left-hand quadrant 3, both torque and speed are negative. In a hoist drive, this condition exists when the motor accelerates its own inertia and the load is accelerated by gravity in the lowering direction. Motor torque is in the same direction as the load torque, gravity pulling the load downward. An equivalent condition exists when the motor drives a friction or inertia load in a direction of rotation, opposite to the one existing in quadrant 1. Power is delivered by the motor to the load. Quadrants 1 and 3 are equivalent, except that direction of rotation is reversed.

Lower right-hand quadrant 4 covers the case when motor torque is positive while speed is negative. In a hoist, for example, motor torque opposes the load torque, which is the pull of gravity. While the motor attempts to hoist the load, the load overhauls the motor, so that actual movement is in the lowering direction. The motor torque restrains the load, that is, the motor develops a braking torque. Thus, in describing hoist performance, this quadrant is often called the braking lowering quadrant. Energy is absorbed by the motor from the load and dissipated as ohmic loss or fed back to the power system. When a motor drives an inertia load, motor torque opposes the overhauling load torque due to the kinetic energy of the inertia load. Quadrants 2 and 4 are equivalent, except for reversal of the direction of rotation.

The control engineer can obtain from the motor designer a set of characteristic curves which describe the performance of the motor in quadrant 1, that is, with torque and speed positive. From these motor curves, and by applying certain basic relations, motor performance in the other quadrants can be calculated.

Basic Relations

The performance of dynamo-electric machines is based on the principle that a conductor through which current flows, while in a magnetic field, is subjected to a deflecting force. The force exerted on the conductor is a function of the product of flux and current. The speed with which the conductor is deflected is related to the counter emf induced in the conductor in such a manner that the counter emf is a function of the product of flux and speed with which the conductor intersects the flux lines. By applying these basic concepts to an electric motor, the following relations can be stated:

1. Torque is a function of the product of armature current and effective field flux. If armature reaction is neglected, it can be assumed that flux is a function of field current. Thus it can be stated that *torque is a function of the product of armature current and field current.*

From the characteristic curve of a given motor, the relation of torque versus armature current can be obtained. If the field current of the motor is known, for any value of field current a factor can be calculated:

$$\frac{T}{I_a} = \text{torque per armature current} = K_T \qquad (1)$$

where T = torque in lb-ft or in per unit,
I_a = armature current in amperes or in per unit.

This factor is assumed to be a constant for any given amount of field current, which is permissible for most practical performance calculations. If a motor is expected to operate with variable field current, a K_T versus field current curve is plotted from the motor characteristic.

2. Generated voltage or counter emf E is a function of the product of speed and effective field flux. As flux is a function of field current, it can be stated that *generated voltage is a function of the product of speed and field current.* As motor speed is of primary interest, it is preferable to express the above relation as *speed is a direct function of generated voltage and an inverse function of field current.*

For a motor which operates motoring, that is, whose armature takes power from the line and converts it into mechanical energy, the counter emf is equal to applied line voltage minus all the voltage drops in series with the armature. The voltage drops consist of resistance drop plus brush drop. The resistance drop includes the drop across external as well as internal resistance. It is proportional to the armature current, that is, the load on the motor. The brush drop is not strictly proportional to load, but for performance calculations it is permissible to assume that the brush drop is due to an equivalent brush resistance which can be lumped in with the armature resistance. The brush drop varies with individual motors and with the grade of brushes used. If no test data are available, it can be assumed to be 2 volts at full load.

The following relation applies to a motor delivering mechanical torque at its shaft:

$$E = V - I_aR \tag{2}$$

where I_a = armature current in amperes or in per unit,
R = total internal and external resistance in ohms or in per unit,
V = applied line voltage in volts or in per unit,
E = motor counter emf in volts or in per unit.

If a motor is overhauled by its load, it absorbs mechanical energy at its shaft and delivers electrical energy to the line or to a resistance load. The motor actually operates as a generator, and the counter emf has to overcome series resistance drop and brush drop. Thus, for a motor that is absorbing mechanical energy at its shaft, this relation exists:

$$E = V + I_aR \tag{3}$$

The characteristic curve of a motor gives the speed as a function of load and field current for a given constant line voltage. If the internal resistance of the motor is known, the counter emf can be calculated, and a factor can be determined:

$$\frac{E}{S} = \text{counter emf per speed} = K_S$$

where S = motor speed in rpm or in per unit.

Factor K_S can be assumed for most calculations to be a constant for a given field current. If a motor is called upon to operate with variable field current, a K_S versus field current curve is plotted from the motor characteristic curve.

Later in this chapter it is shown how the K_T and K_S curves are used to calculate motor performance.

Maximum Torque and Commutation Limit

In the preceding paragraphs it has been stated that K_T is a constant for any given field current. This holds true only as long as the armature current does not greatly exceed rated full-load current. At current values greatly in excess of rated current, the effect of armature reaction becomes so great that the effective flux is reduced below the value normally corresponding to the exciting field current. In fact, armature reaction may become so great as to reduce the flux to zero. Increasing the armature current beyond a certain value produces an increasingly smaller gain in torque.

The output of a d-c motor in terms of torque is limited by two characteristic quantities. One is the maximum torque which the motor is able to deliver electrically. It may be as high as five times rated torque at full field. This high torque, in practice, cannot be realized as shaft output because it would be impossible to commutate the large amount of current coincident with that amount of torque. However, when the motor is used in circuits affecting the distribution of current in the field and armature branch, it may happen that maximum torque is greatly reduced, even below normal torque, with armature currents well within the commutating ability of the motor. When designing control equipment for a given motor, the control designer must ascertain the maximum torque from its design data and he must make certain that the maximum torque is never exceeded while motor connections are changed during transition between control points. Otherwise, the motor may stall while driving a load, or it may run away while being overhauled.

Of equal, if not greater, importance is the commutation limit. If the armature current is increased beyond a certain limit, the commutating poles saturate, the commutating pole flux does not neutralize the cross flux due to armature reaction, and the brushes commutate no longer in the neutral zone. These conditions result in sparking or arcing of the brushes, which leads to excessive wear of brushes and commutator and even to arc-overs between brush holders of opposite polarity. Thus the amount of torque which can be utilized at the motor shaft may be limited by the amount of current the motor is able to commutate. The commutation limit, which varies with speed and field current, is a definite characteristic of each d-c motor. The control designer must know this limitation and lay out the control equipment accordingly.

SERIES MOTORS

The simplest and most versatile d-c motor is the series wound motor. Its basic connection and a typical speed-torque curve are shown in Fig. 10. It derives its name from the fact that the field is connected in series with the armature. From the speed-torque curve the following conclusions which govern the field of application for this type of motor can be drawn:

1. The motor has a high maximum torque at zero speed and is thus ideally suited for starting heavy loads.

2. The drooping characteristic causes the motor to slow down when subjected to overloads. This means that the power demand

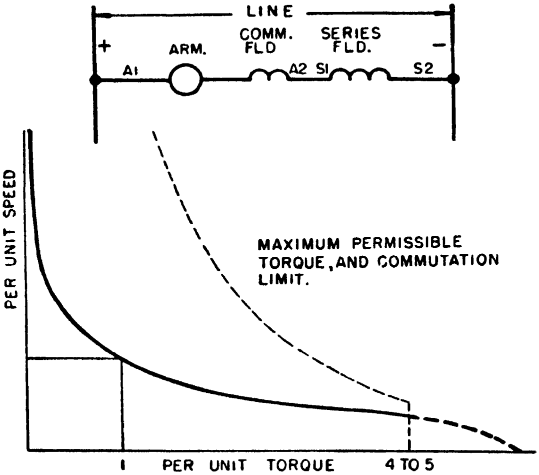


FIG. 10. Basic connections and typical speed-torque curve of a d-c series motor.

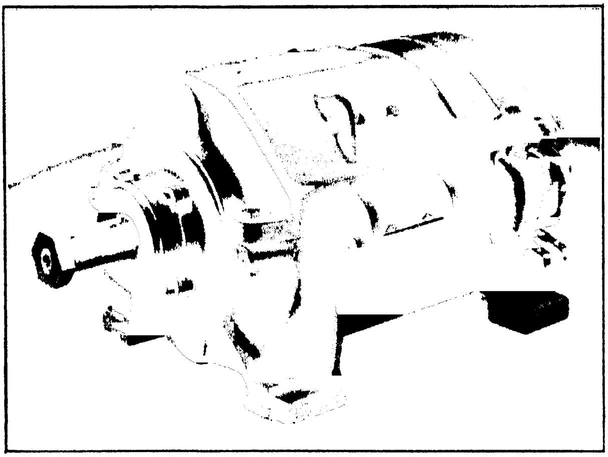


FIG. 11. Mill type d-c series motor.

from the line does not rise in proportion to the torque but at a lesser rate. Series motors are not at all suited for drives where uniform speed is required over a wide range of loads.

3. At no load the speed may rise very high, and a completely unloaded motor will "run away." Thus series motors should

not be used on drives where the torque on the motor shaft may drop below 0.15 of rated torque.

The above characteristics make the series motor especially well suited for intermittent heavy-duty material handling and steel mill auxiliary drives such as cranes, ore and coal bridges, unloaders, transfer cars, and the like. Many series motors used in industry are of a type, usually designated as *mill motors* or *armored motors*. The specific data given in subsequent paragraphs on motor performance are based on design data for mill motors.

Figure 11 is a view of a typical mill motor.

Parallel Operation

The drooping speed-torque characteristic makes series motors well suited for dividing load evenly when operating in parallel, that is to say, when two or more motors are coupled mechanically to the same drive system. As there are always slight variations in the mechanical and electrical characteristics of different motors of the same rating and the same design, such as friction and internal resistance, no two motors ever have exactly the same speed-torque curve. What happens when two series motors operate in parallel is illustrated by Fig. 12.

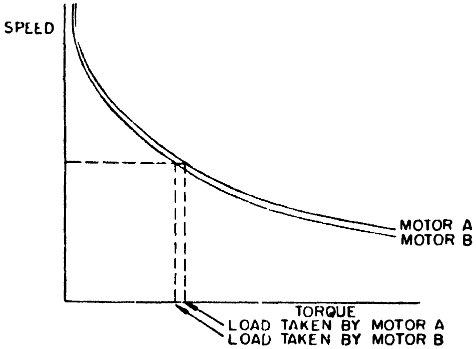


FIG. 12. Load division of two series motors operating in parallel.

As the two motors must operate at the same speed, the torque delivered by the motors is not the same. However, as an appreciable variation in speed corresponds to a small variation in torque, there is only a slight difference in the torques delivered by the two motors. Certain precautions, explained in Chapter 18, must be observed in laying out the control sequence.

Reversing

The direction of motor rotation corresponds to the direction of its counter emf with respect to its flux. Hence the direction of rotation can be reversed by reversing either the armature or the series field, but not both. Figure 13 shows how a series motor can be reversed.

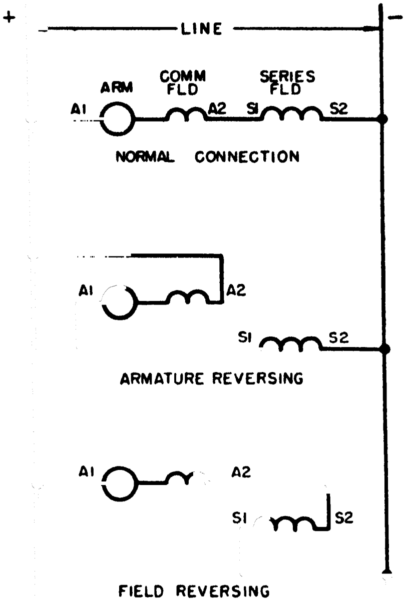


FIG. 13. Methods of reversing d-c series motors.

As far as the principle of operation is concerned, it is immaterial whether the armature of the field is reversed. However, when details of reversing control circuits are worked up it is found that often reversing of the armature requires simpler control connections. Therefore it has become accepted practice to reverse the armature on reversing controllers.

Motor Performance Curves[2, 3]

In the following paragraphs means are discussed for controlling the performance of series motors, and methods to calculate performance curves are presented. To make the results applicable generally, they are given on a per unit basis, where unity represents base values of speed, torque, current, and voltage. By substituting numerical values pertaining to specific motors in place of unity, the per unit values can be translated into actual performance data.

Base quantities as used in these calculations are defined as follows:

Base current = rated full-load current

Base torque = rated full-load torque

Base voltage = line voltage

Base speed = rated speed at rated torque

To control the performance of a d-c series motor, resistance is connected in various parts of the motor circuit. Since all other quantities describing motor performance are expressed in per unit, it is convenient to express resistance in per unit. Base resistance **R** is defined as that amount of resistance which, when connected across line voltage, draws base current. In other words,

Base resistance = line voltage divided by base current

In the per unit system, as well as numerically, the following relation holds true

$$R = \frac{V}{I_a} \tag{4}$$

It is customary for motor designers to give the characteristics of a motor as curves plotted versus armature current. Figure 14 is a typical characteristic of a 30-minute rated mill type motor, in which speed and torque in per unit are plotted versus armature current (which in the case of the series motor equals field current) in per unit.

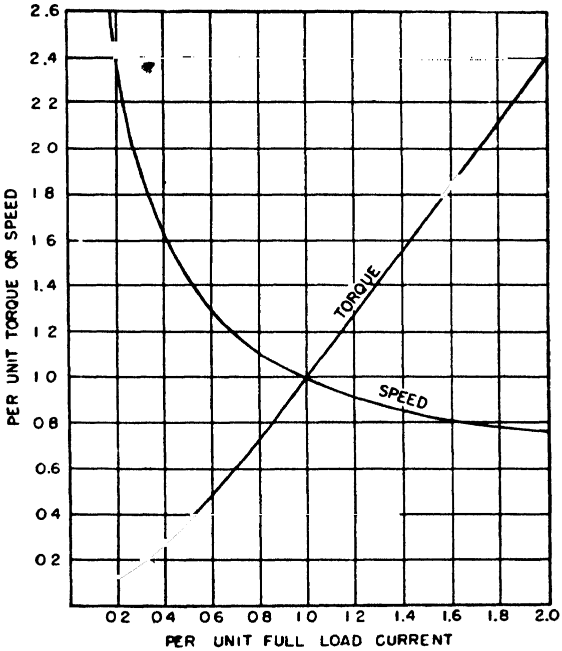


FIG. 14. Typical characteristic curves of a 30-minute rated mill type d-c series motor.

From such a characteristic for any given motor, factors K_T and K_S can be calculated as a function of field current. For each value of armature current, factor K_T can be determined directly. With the internal resistance, the counter emf can be calculated, from formula 2, for each value of current, thus obtaining factor K_S.

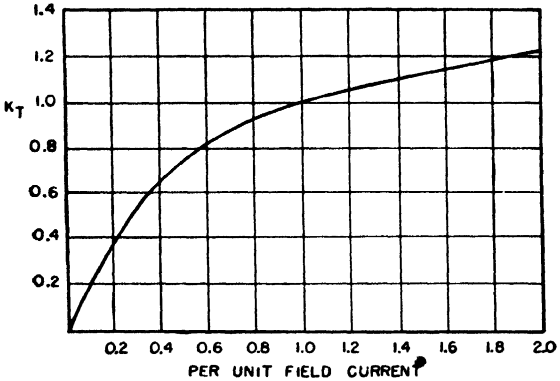


FIG. 15. Factor K_T for typical mill type d-c series motor.

In Fig. 15, factor K_T is plotted versus per unit field current. When performance data of the motor are expressed in per unit, factor K_S bears a definite relation to K_T. Normal emf E_N, which is generated with base current flowing through the motor, is determined as

$$E_N = V - I_a R_i \tag{5}$$

where V = line voltage = 1,
I_a = base current = 1,
R_i = per unit internal resistances.

In per unit, normal emf can thus be expressed as

$$E_N = 1 - R_i \qquad (6)\ \blacksquare\ *$$

The relationship between K_T and K_S is

$$K_S = K_T E_N$$

$$= K_T(1 - R_i) \qquad (7)\ \blacksquare$$

For instance, if a motor has an internal resistance of 0.1, K_S equals $0.9K_T$. When field current, armature current, and generated emf are

* Formulae which are correct only on a per unit basis and cannot be used for numerical calculations are followed by the symbol ■. Formulae which cannot be used for per unit calculations and only for numerical calculations are followed by the symbol ●. (See page 56.) All other formulae in this book hold true for both per unit and numerical calculations.

known for any motor operating condition, torque and speed can be calculated as follows:

$$T = K_T I_a \tag{8}$$

and

$$S = \frac{E}{K_S}$$

$$= \frac{E}{K_T(1 - R_i)} \tag{9}$$

To calculate speed-torque curves for a specific motor from the motor characteristic curves, it is necessary to know its internal resistance. In Fig. 16 the per unit internal resistance of mill type d-c series motors is plotted as a function of motor horsepower.

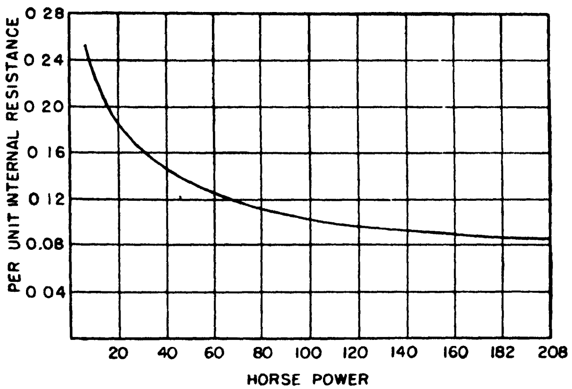


Fig. 16. Internal resistance of mill type d-c series motors.

In subsequent paragraphs various methods of controlling a series motor are discussed, and speed-torque curves are given together with methods for calculating them. The following symbols are used to represent the component parts of the motor circuit and the performance data:

V = line voltage, defined as unity
E = emf of motor
R_i = internal resistance of motor, assumed at 0.1
R_{ia} = internal resistance of armature and commutating field, assumed at 0.07
R_{if} = internal resistance of series field, assumed at 0.03
R_s = resistance in series with motor
R_p = resistance in parallel with motor or armature
R_a = resistance in series with armature

R_f = resistance in series with series field
I_s = current in circuit in series with motor
I_a = current in armature circuit
I_f = current in series field circuit
T = motor torque
S = motor speed

Speed Control by Series Resistance

Inserting resistance in series with the motor affects the motor speed-torque characteristic in the following manner. For each value of current the voltage drop is increased by the amount of drop in the series resistance. Counter emf E can be determined as follows:

$$E = V - (I_aR_t + I_aR_s) \tag{10}$$

For each value of current, which also means for each value of torque, the emf is reduced by the drop I_aR_s, and the speed at that torque is reduced correspondingly.

A graphical method to determine motor performance is indicated in Fig. 17. Let the ordinate be emf E, unity being line voltage V, and

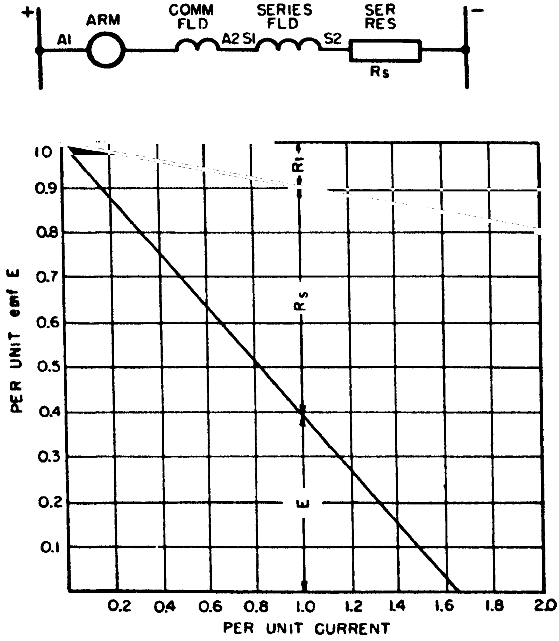


FIG. 17. Graphical method of determining effect of series resistances on performance of d-c series motor.

let the abscissa be per unit current. On the ordinate representing unity current, mark off R_i and R_s in per unit and draw a straight line from the unity speed-zero torque point through the point thus found. Where this line intersects with the ordinates of current, E can be read for any value of current. With K_T determined from Fig. 15, torque and speed can be calculated for any assumed current from formulae 8 and 9.

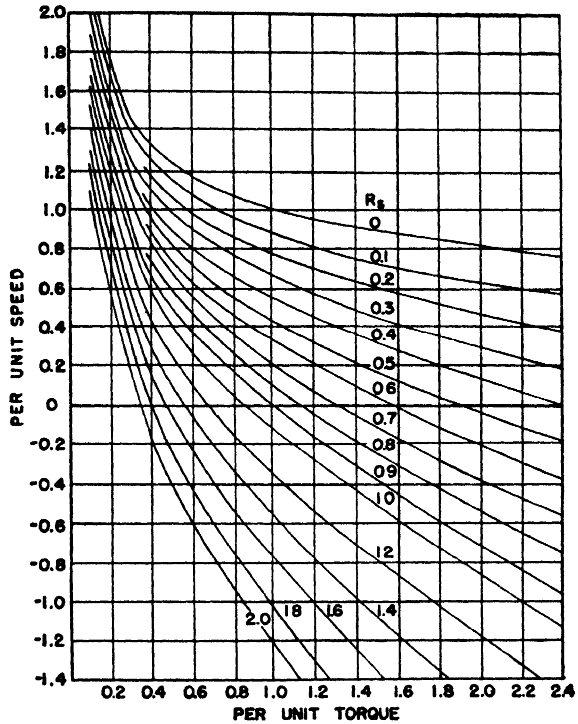


FIG. 18. Speed-torque curves of mill type d-c series motor with variable series resistance.

In Fig. 18 speed is plotted versus torque for various amounts of series resistance. These curves are plotted assuming an internal resistance $R_i = 0.1$. These curves can be used for motors with different internal resistance by lumping the difference between actual R_i and 0.1 with the external resistance.

With high amounts of series resistance, the speed-torque curves extend into quadrant 4, where torque is positive but speed is negative, that is to say, where the motor retards a load by developing a torque opposing the overhauling torque of the load. Resistance in series with the motor is well suited to control the counter torque developed when the motor connections are reversed while the motor is still running forward, that is to say, when the motor is plugged to rest. It is not suited to control a load under the influence of gravity, such as a load on a hoist, since small variations in load cause wide variations in speed.

Shunted Motor Connection

Connecting resistance in parallel with the armature and the field of the series motor affects motor performance only if shunt resistance is used in combination with series resistance. For a given amount of armature current, which means for a given amount of torque, emf and speed are reduced, because the voltage drop across the series resistance is increased by the extra current drawn through the shunt resistance.

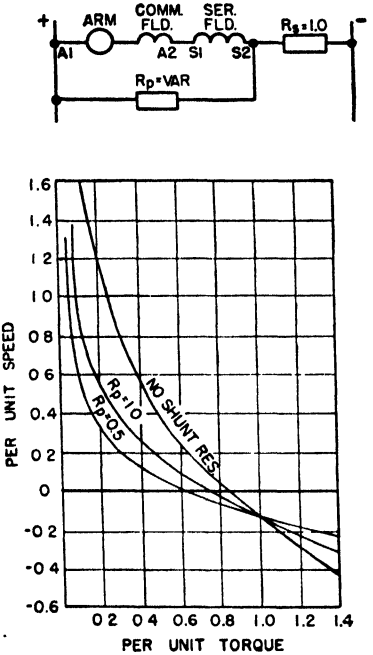


FIG. 19. Shunted motor connection. Speed-torque curves for variable shunt resistance.

The following relations describe motor performance:

$$I_a = I_s - \frac{V - I_s R_s}{R_p} \quad (11)$$

$$E = V - (I_s R_s + I_a R_t) \quad (12)$$

If various amounts of I_s are assumed, corresponding values of I_a and E can be calculated, from which T and S can be determined by formulae 8 and 9. In Fig. 19 speed-torque curves are plotted for a series resistance of 1.0 and shunt resistances of 0.5 and 1.0. For comparison, the curve for no shunt resistance is also shown.

Since field current and armature current are the same, field current drops to a very low value when the motor is unloaded, and the motor may run away. In other words, a shunted motor connection does not limit the no-load speed of the motor. Starting torque at standstill is somewhat reduced, because the increased voltage drop across the series resistance reduces the voltage across the armature, and thus reduces the armature current at starting. At intermediate loads, the increased drop across the series resistance reduces the emf of the motor, and consequently the speed. Over a certain torque range, the speed-torque curves are more stable, that is, a smaller variation in speed corresponds to a given variation in torque. When a controller using the shunted motor connection is designed, the rating of the series resistor must take into consideration the extra amount of current drawn by the shunt resistor.

Shunted Armature Connection

If resistance is connected in parallel with the armature of the motor only, and not its field, armature and field current no longer

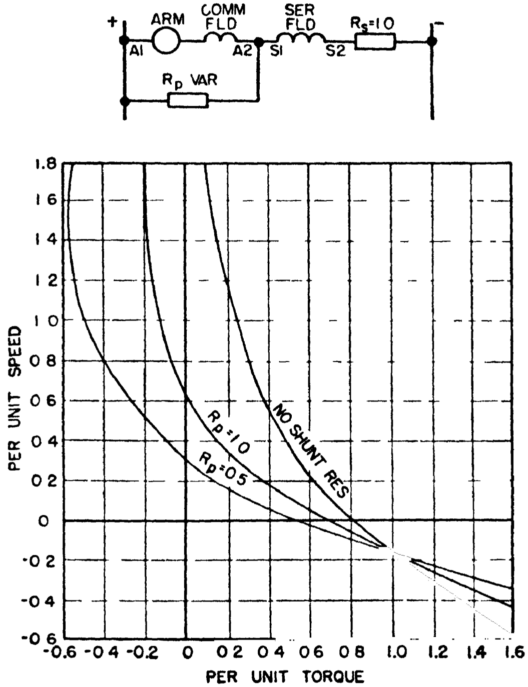


Fig. 20. Shunted armature connection Speed-torque curves for variable shunt resistance.

are equal. At no load, with zero armature current, the field current does not become zero. Thus the no-load speed of the motor becomes a definite value, and the motor does not run away when unloaded.

The following relations exist for armature current and emf:

$$I_a = I_f - \frac{V - I_f(R_{tf} + R_s)}{R_p} \tag{13}$$

$$E = V - [I_f(R_{tf} + R_s) + I_a R_{ta}] \tag{14}$$

In order to determine the speed-torque curves, various amounts of I_f are assumed and corresponding values of I_a and E are calculated.

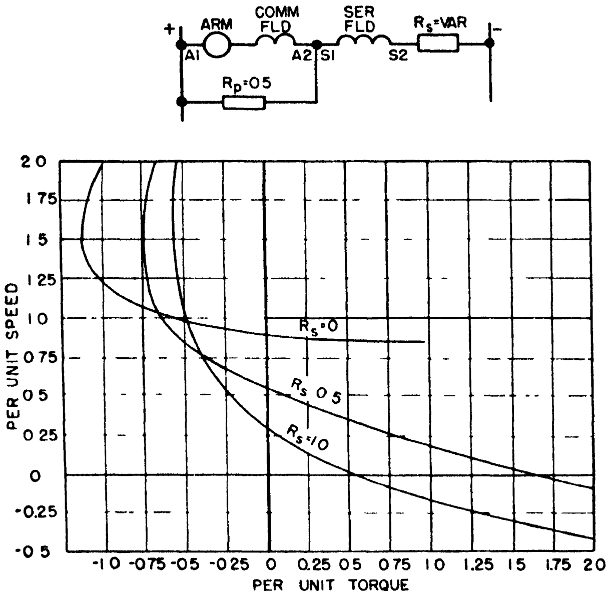


FIG. 21. Shunted armature connection. Speed-torque curves for variable series resistance.

Torque and speed are determined by using formulae 8 and 9. Note that values of K_T must be read for values of field current and not armature current.

In Fig. 20 speed-torque curves are plotted for a constant series resistance 1.0 and variable shunt resistance. Figure 21 shows corresponding curves for constant shunt resistance 0.5 and variable series resistance. If a negative torque is impressed on the motor (quadrant 2), a given speed corresponds to a definite retarding torque, and thus armature shunting is well suited to decelerate a series motor from a high speed to a lower speed.

When armature shunting control is used it must not be overlooked that the series field carries more current than the armature. Armature shunting is therefore used only intermittently, to avoid overheating of the field. Its principal application is to provide fast and smooth retardation and to obtain stable slow speeds at light loads.

Series Generator Connection

If the armature and field are connected in series with resistance in a loop, and if the motor is driven by an overhauling load, the motor acts as a self-excited series generator. The relation between emf and current flowing in the loop circuit is

$$E = I_a(R_t + R_s) \tag{15}$$

For a given amount of series resistance, a definite speed is obtained with a given amount of torque.

Speed-torque curves are calculated by assuming various amounts of armature current and determining corresponding values of E. As armature and field current are the same, torque corresponding to I_a can be read directly from Fig. 14. Speed is calculated from E by using formula 9. The resultant speed-torque curves are shown in Fig. 22 for various amounts of series resistance.

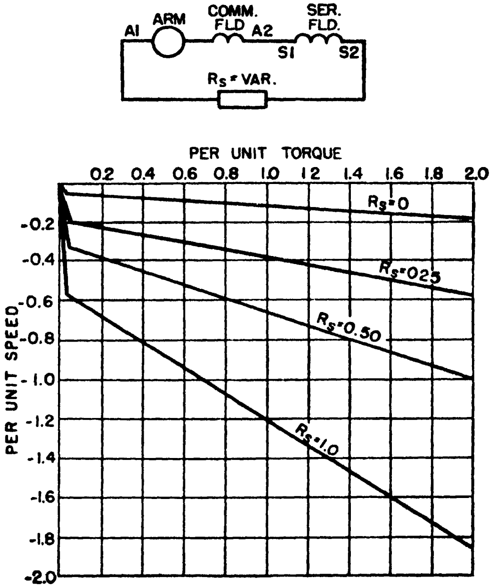


Fig. 22. Series generator or emergency dynamic braking connection. Speed-torque curves for variable series resistance.

It is essential that the polarity of the field and the armature be chosen so that the armature current flows in a direction to build up the residual flux in the field structure. In other words, the armature current must flow in the same direction in which current flowed through the series field before the series generator connection was established. If this precaution is not taken, the armature current reduces the residual flux to zero, no self-excitation takes place, and no torque is developed.

In Fig. 22 speed is indicated as negative for the following reasons. Assume that the motor was connected previously to the line with terminal $A1$ positive and current flowing through the motor from $A1$ to $A2$ to $S1$ to $S2$. With this connection, speed is assumed to be positive, which corresponds to the manner in which preceding speed-torque curves are given. While the motor was connected to the line, its emf was of opposite polarity to line voltage. With series generator connection, a braking torque can be obtained only when $A1$ is positive, which means that the motor must turn in the opposite direction of rotation to obtain correct polarity and current flow through the series field from $S1$ to $S2$.

The series generator connection is widely used as an emergency dynamic braking connection in case of power failure, especially on crane hoists. The motor, connected as a series generator, cannot stop an overhauling load; however, an uncontrolled run-away condition is avoided. The torque of the overhauling load cannot accelerate the motor beyond a definite speed.

Shunt Generator Connection

If the field, in series with a resistance, is connected across the line and the armature is also connected in series with a resistance, the motor acts as a separately excited shunt generator, when driven by an overhauling load. The relation between armature current and emf is

$$E = I_a(R_{ia} + R_s) \tag{16}$$

Since the field current is constant, K_T is constant and the speed-torque curves are straight lines. They are shown in Fig. 23 for the case in which the resistance limits the shunt field current to unity. The higher the resistance in series with the armature is chosen, the higher the speed obtained for a given overhauling torque.

As compared with the series generator connection, the shunt generator connection requires that power from the line is available in order to supply excitation to the field. This connection can be used to advantage to retard a load. It is used primarily on drives where the load is not under the influence of gravity, such as crane trolleys, in order to decelerate the trolley rapidly.

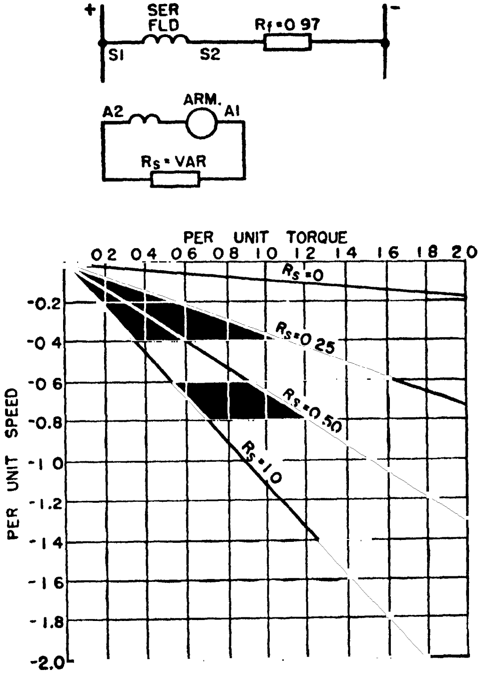


Fig. 23. Shunt generator or dynamic braking connection. Speed-torque curves for variable series resistances.

Dynamic Braking Lowering Connections

A series motor, with field and armature connected in series, is not suitable for the control of a load which overhauls the motor under the influence of gravity, such as the load on a crane hoist. Good control of the lowering speed can be obtained when the field is connected in parallel with the armature, as field and armature current can then be varied independently of each other, and speed-torque curves can be obtained which are well suited to lower overhauling loads.

Consider first the case shown in Fig. 24, where the field is connected to the line through resistance, which is necessary to prevent injuriously high currents from flowing through the field. This means that the field current is determined only by the amount of resistance R_f in series with the field. If the armature is connected across the line without resistance in series with it, the relation between armature current and emf is

$$E = V + I_a R_{ia} \tag{17}$$

As K_T is constant for a given value of field current, the speed-torque curves are straight lines.

Speed-torque curves as shown in Fig. 24 are very satisfactory for lowering a load, since the change in speed is small for a wide change

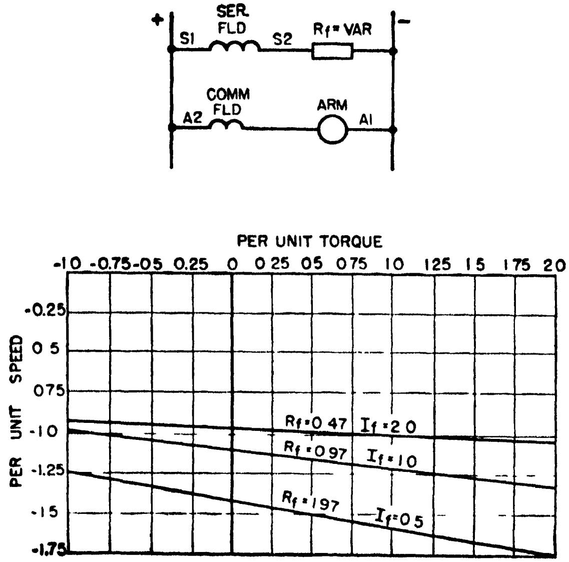


Fig. 24. Dynamic braking lowering connection Speed-torque curves for variable field resistance, no armature resistance.

in load. Speed control is obtained by varying the resistance in series with the field. Increasing the amount of R_f, that is, weakening the amount of field current, increases the lowering speed.

Although the straight shunt field connection obtains good results as a running connection, it is not well suited for acceleration or retardation. It is impossible to obtain low speeds without passing very high current through the field winding. For this reason, connections using resistance in series with the armature or in series with both armature and field are preferred because they provide better lowering control.

Another reason why straight shunt field connections should be used with caution is that, with the field carrying considerably less current than the armature, the motor will become unstable. So far the calculation of speed-torque curves has been considered under the assumption that armature reaction is negligible and that field current is a true measure of effective field flux. This does not hold true if field current is much lower than armature current. It is then no longer permissible to assume K_T to be a function of field current only. When the motor acts as a generator, K_T may become much smaller than Fig. 15 indicates. The maximum retarding torque which the motor may develop is definitely limited, and actual lowering speeds under load are higher than shown in Fig. 24.

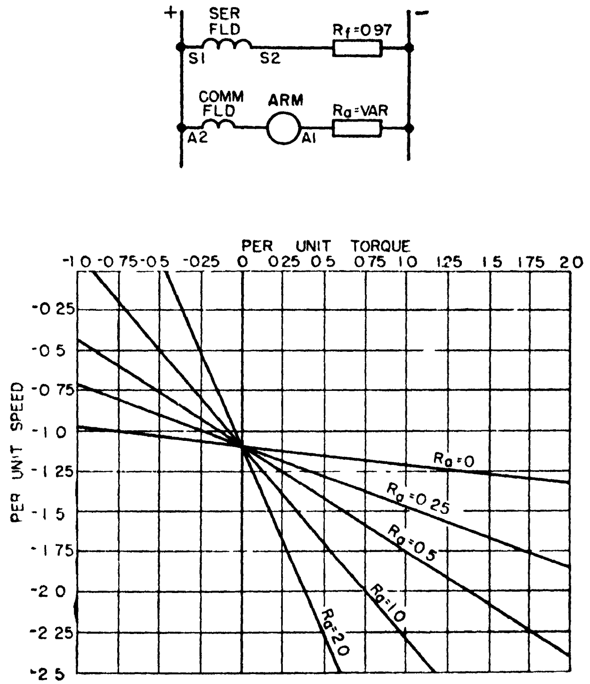


Fig. 25. Dynamic braking lowering connection. Speed-torque curves for normal field current, variable armature resistance.

This problem is discussed in greater detail under "Stability Limit," page 47.

If the field current is held constant, but a variable amount of resistance is inserted in the armature circuit, the voltage drop across the armature circuit is increased for a given amount of torque, and thus the speed increases with increasing amount of armature resistance. Since for constant I_f, K_T is assumed constant, armature current and emf are a direct measure of torque and speed, respectively. The armature current-emf relation is

$$E = V + I_a(R_{ta} + R_a) \tag{18}$$

Speed-torque curves are straight lines, as plotted in Fig. 25. They are steeper than the curves shown in Fig. 24, and they are not so desirable as lowering curves, since the speed varies considerably with torque changes. However, as the curves intersect with the zero speed line at comparatively low torque values, armature resistance can be used advantageously to control acceleration to the more stable curves with no resistance in the armature circuit.

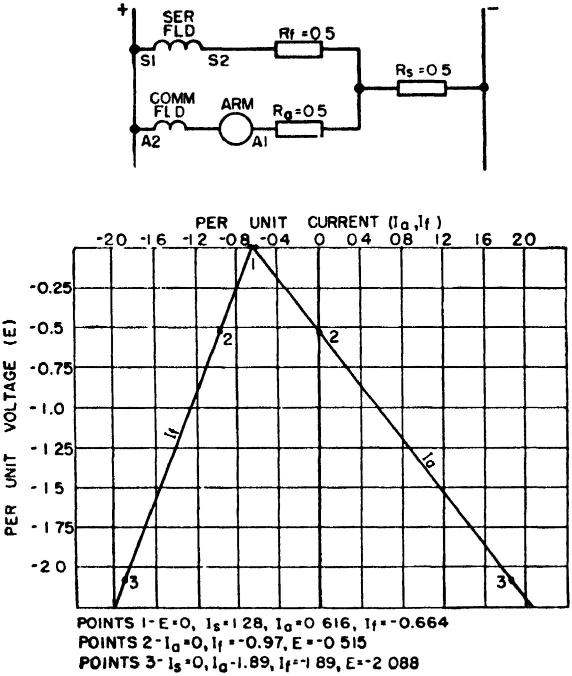


FIG. 26. Graphical method for determining speed-torque curves for dynamic braking lowering connection.

Widely used is a motor connection with resistance in series with armature and field, as before, but with an additional amount of resistance in series with both armature and field. Field current thus is no longer constant but varies with load, because the voltage drop across the series resistance varies with load. Voltage across the field circuit likewise varies with load. The following relations exist for current in the various branches of the motor circuit:

$$V = I_f(R_{if} + R_f) + I_sR_s = 1 \tag{19}$$

$$E = I_f(R_{if} + R_f) + I_a(R_{ia} + R_a) \tag{20}$$

$$I_s = I_f + I_a \tag{21}$$

To calculate speed-torque curves, I_f, I_a, and E have to be known for each speed and torque point to be plotted. The equations above show that the relations between E and the various currents are linear. A simple graphical method for determining E, I_f, and I_a is given in Fig. 26, and, as an example, R_a, R_f, and R_s are each assumed to be 0.5. The object of this method is to determine the straight line functions for I_a and I_f versus E. Three points on each line can be determined as follows:

1. Assume $E = 0$. Series current through armature and field can be expressed as

$$I_S = \frac{V}{R_s + \dfrac{1}{\dfrac{1}{R_{ia} + R_a} + \dfrac{1}{R_{if} + R_f}}} \tag{22}$$

As the voltage drop across the field and armature circuits must be the same,

$$I_a = \frac{I_s(R_{if} + R_f)}{R_{ia} + R_a + R_{if} + R_f} \tag{23}$$

$$I_f = I_s - I_a \tag{24}$$

2. Assume $I_a = 0$. Series and field current are equal.

$$I_f = I_s = \frac{V}{R_s + R_{if} + R_f} \tag{25}$$

E is equal to the voltage drop across the field circuit.

$$E = I_f(R_{if} + R_f) \tag{26}$$

3. Assume $I_s = 0$. Field and armature current are of equal magnitude but opposite direction.

$$-I_a = I_f = \frac{V}{R_{if} + R_f} \tag{27}$$

$$E = V + I_a(R_{ia} + R_a) \tag{28}$$

Plotting the three points of I_a and I_f versus E gives the straight-line curves of Fig. 26. For various values of E, corresponding values of I_f and I_a are read. For values of I_f thus obtained corresponding values of K_T are obtained from Fig. 15. Torque and speed are then calculated, using formulae 8 and 9.

With this method of calculation, speed-torque curves can be plotted for various combinations of series, armature, and field resistance. In Fig. 27 curves are plotted for variable field resistance, series resistance of 0.5, and no armature resistance. As it is to be expected, speed increases with increasing field resistance. These curves resemble Fig. 24 in their general shape, but the addition of series resistance in the motor circuit has the following effect:

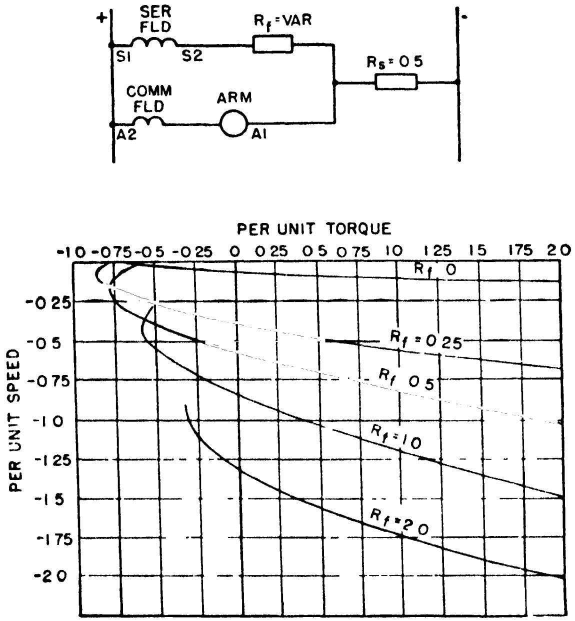


FIG. 27. Dynamic braking lowering connection. Speed-torque curves for 0.5 series resistance, no armature resistance, variable field resistance.

1. Negative torque is reduced; thus this connection can be used for control of acceleration.
2. No-load speed is somewhat reduced.
3. The curves show more droop, that is, speed change with load change; but at high loads the curves tend to become more stable.

Although this flattening out of the curves at high loads is desirable for lowering variable loads, it is an undesirable feature when a load is to be decelerated. Introducing resistance in series with the armature steepens the curves and thus reduces torque and current peaks during deceleration. In Fig. 28 speed-torque curves are plotted for the same condition as in Fig. 27, except that resistance of 0.5 is added in series with the armature. A comparison of these curves with corresponding curves of Fig. 27 shows the following difference:

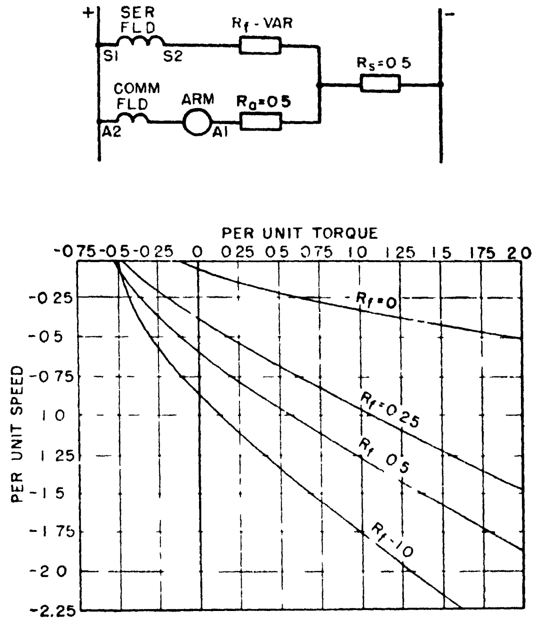


Fig. 28. Dynamic braking lowering connection. Speed-torque curves for 0.5 series resistance, 0.5 armature resistance, variable field resistance.

1. With field resistance between approximately 0.25 and 1.0, negative starting torque changes very little with field resistance.
2. Armature resistance has no effect on no-load speed, as I_a is zero, and thus armature drop is zero.
3. With increased load, the curves show a more pronounced droop, which makes them less desirable as running curves but desirable as intermediate decelerating curves.

To illustrate the effect of varying amounts of resistance in series with the armature, speed-torque curves are plotted in Fig. 29 for field

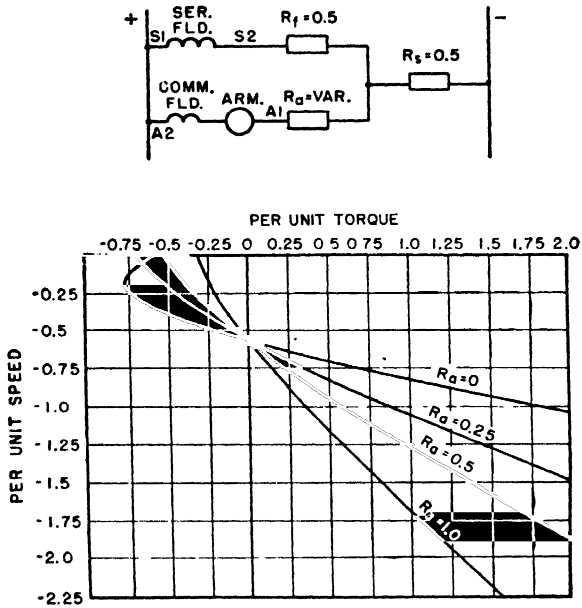


FIG. 29. Dynamic braking lowering connection. Speed-torque curves for 0.5 series resistance, 0.5 field resistance, variable armature resistance.

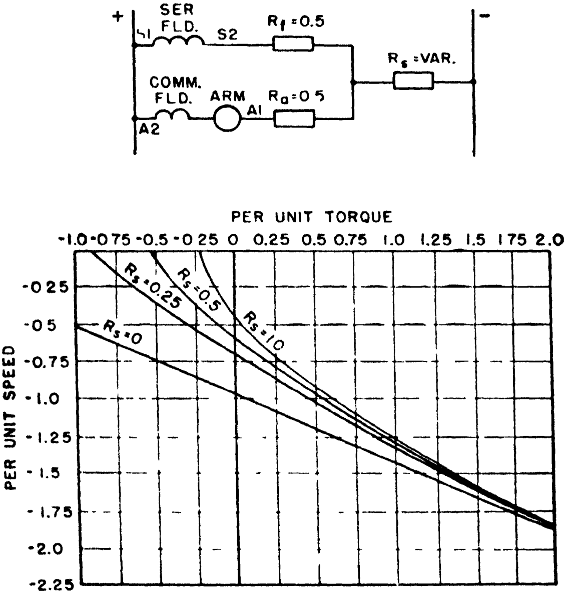


FIG. 30. Dynamic braking lowering connection. Speed-torque curves for 0.5 armature resistance, 0.5 field resistance, variable series resistance.

resistance of 0.5, series resistance of 0.5, and variable armature resistance. The no-load speed point of all curves is the same, as armature current is zero and armature resistance causes no voltage drop. Increasing the amount of armature resistance increases the steepness of the curves. Greater speed changes correspond to given load changes, and the available negative torque is decreased.

What happens when the amount of series resistance is varied is shown by the speed-torque curves of Fig. 30. With no series resistance, the speed-torque curve is a straight line such as shown in Fig. 25. Adding series resistance reduces the no-load speed and the negative starting torque. At higher loads, the curves approach asymptotically the straight-line curve for zero series resistance.

Stability Limit [1]

Speed-torque curves shown so far in this chapter have been calculated under the assumption that armature reaction is negligible, that field current of the motor is a true measure of effective flux, and that K_T is only a function of field current. When dynamic braking connections are used, the motor may operate with a field current considerably smaller than its armature current. Armature reaction then has a pronounced effect in reducing the effective flux while the motor is acting as a generator. This causes the speed with overhauling loads to be higher than the calculated value. Also the maximum retarding torque, which the motor is able to develop, is limited.

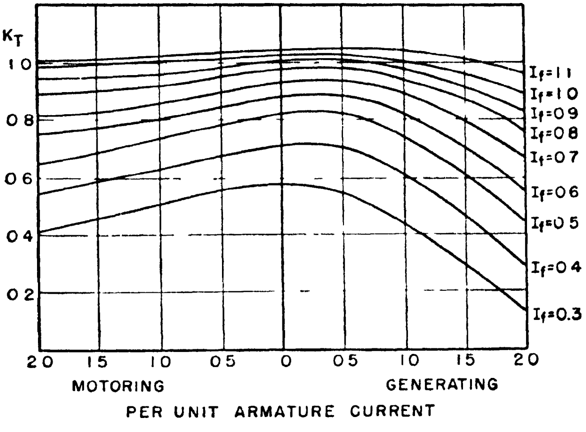


FIG. 31. Factor K_T for variable field and armature current.

When armature current is high and field current is reduced below normal, factor K_T not only is a function of field current, but also varies with armature current. The effect of armature reaction is such that increasing arrmature current reduces K_T below the values given in Fig. 15. In Fig. 31 curves of K_T versus armature current are plotted for varying amounts of field current I_f, for an average mill type motor. The curves are drawn both for motoring, that is, the motor driving a load, and generating, that is, the motor being overhauled by a load. For any particular motor, curves as given in Fig. 31 must be obtained from test data.

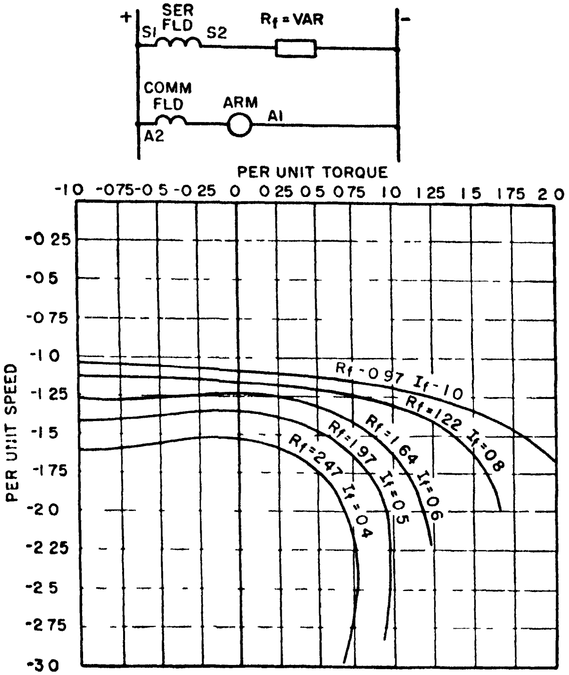


FIG. 32. Dynamic braking lowering connection Speed-torque curves showing motor stability limit with weakened field, no series resistance

What armature reaction means to motor performance is indicated by the curves of Fig. 32. These curves are drawn for the same circuit as used in Fig. 24, and a comparison of the two sets of curves is of interest. The speed-torque curves are actually not straight lines, but as the overhauling torque increases, the motor speed increases considerably above the speed indicated by the straight-line curves. Also, for each amount of field strength there is a corresponding torque beyond which the motor is unable to restrain a load. This maximum torque is the stability limit of the motor, which must not be exceeded.

Otherwise a run-away condition exists, which means that no-load speed may not be increased at will by field weakening.

When motor performance is judged with respect to stability, it is important to consider not only steady state but also transient conditions. Torque peaks, which may occur during acceleration, may exceed the stability limit of the motor and cause a run-away condition, even though the steady state load on the motor is well within the stability limit.

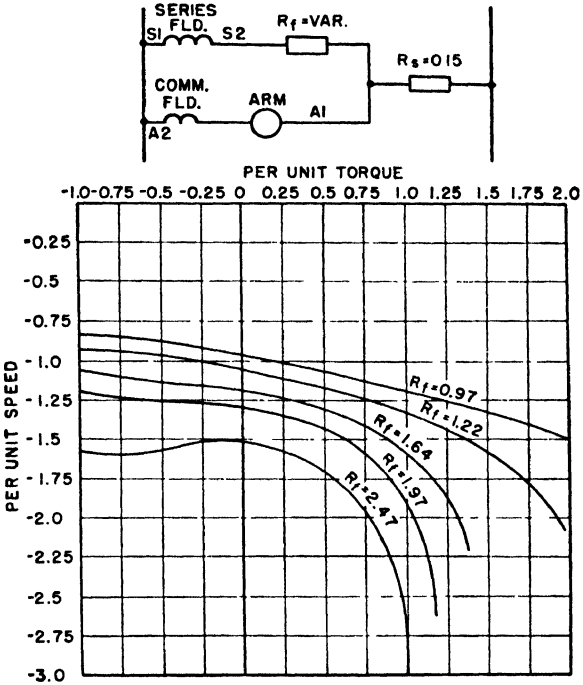


FIG. 33. Dynamic braking lowering connection. Speed-torque curves showing motor stability limit with weakened field, 0.15 series resistance.

The stability limit of a motor can be increased by adding a comparatively small amount of series resistance, with the following effect. With an overhauling load, the motor acts as a generator and current flows from the armature into the system. When the torque is high, that is to say, with high armature current, the voltage drop in the series resistance causes a greater amount of current to flow through the field circuit so that the field is strengthened as the overhauling load increases. In Fig. 33 speed-torque curves are plotted when a series resistance of 0.15 has been added to the circuit

A comparison of Figs. 32 and 33 shows that the additional series resistance has little effect on the curves at light and moderate loads. However, the series resistance has a noticeable effect in increasing the torque at which the stability limit occurs. As a safeguard against run-away under steady load or under torque peaks, a certain amount of series resistance should be used when laying out a dynamic braking lowering controller.

SHUNT MOTORS

The shunt motor derives its name from the fact that the field is connected to the line in parallel with the armature. Its flux, armature reaction neglected, is independent of the load or armature current and determined solely by the amount of current flowing through the shunt field. It follows that, within the normal load range of the motor, torque is proportional to armature current and speed is nearly constant, except for the natural regulation due to the voltage drop through the armature circuit.

Since speed is inversely proportional to flux, the speed of a shunt motor can be varied by changing the amount of shunt field current. Standard shunt motors are rated as either constant speed or adjustable speed motors. Constant-speed motors are built to operate with constant field current at a speed called basic speed. Adjustable-speed motors are designed to operate over a given speed range obtained by weakening the shunt field current. A speed range up to four times basic speed can be obtained with standard motors, although higher speed ranges have been obtained with specially designed motors.

In connection with the calculation of performance curves for series motors it has been shown that, when a motor operates with reduced field strength, armature reaction reduces the effective flux. The same holds true for shunt motors. The effect of armature reaction is to increase the motor speed under load above the speed at which the motor would operate if there were no armature reaction. In fact, the speed under load might rise above the no-load speed. For this reason many adjustable-speed motors and some constant-speed motors are built with a stabilizing winding, which is a series field winding of a few turns, designed so that it overcomes the demagnetizing effect of armature reaction. At basic speed and normal load the stabilizing field has little effect on motor performance. However, at high speed and weakened shunt field strength, and at high loads, the stabilizing field strengthens the effective flux appreciably, which results in a drooping speed-torque characteristic of the motor over a wide range of load.

In Fig. 34 the basic connections and a typical speed-torque curve are shown for a general-purpose, continuously rated shunt motor. The shape of this curve indicates that the shunt motor differs from the series motor in the following respects:

1. Maximum permissible torque is considerably less than for the series motor, making the shunt motor less suitable for starting heavy loads.

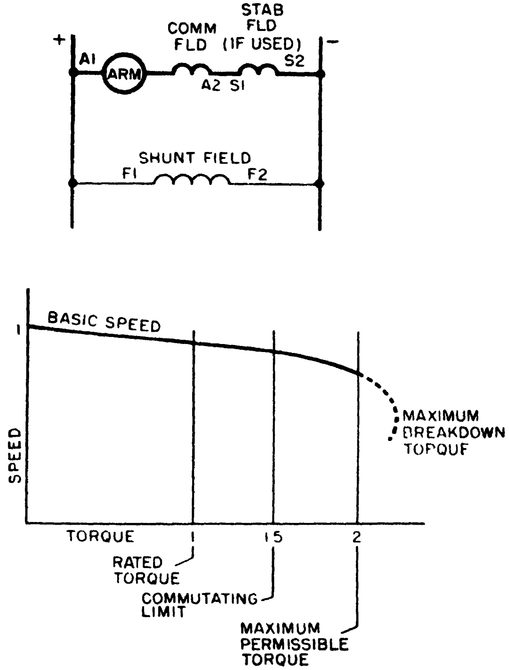


Fig. 34. Basic connections and typical speed-torque curve of a general-purpose, constant-speed d-c shunt motor.

2. Speed varies much less with load, so that the shunt motor is better suited for continuously running drives, where a substantially constant speed over a wide range of loads is desired.
3. No-load speed is definitely limited, which means that a completely unloaded shunt motor does not run away.

For convenience in calculating motor performance, the no-load speed with full-field excitation, rather than the full-load speed, is called base speed or unity. It is the basis on which speed is expressed in subsequent paragraphs. Base torque, of course, is the rated full-load torque of the motor.

In Fig. 34 certain limitations in the application of the shunt motor are indicated. The commutating limit is the amount of torque the motor can deliver for one minute without injurious sparking. The maximum permissible torque is the amount of torque which the motor is guaranteed to deliver instantaneously without injury to the mechanical parts, the commutator, and the brushes. This torque must not be exceeded when switching between controller points. The maximum *break-down torque* the motor is able to develop electrically is still higher, the exact amount varying greatly with different motor designs. This break-down torque is of theoretical interest only because commutation limitations prevent its being utilized at the motor shaft.

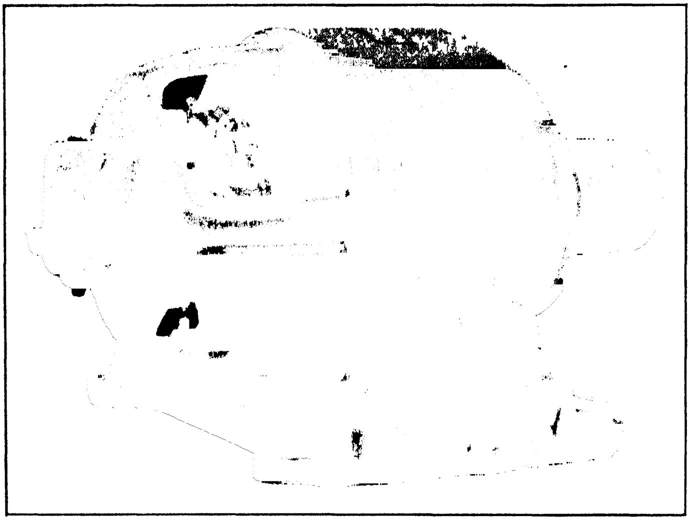


FIG. 35. General-purpose d-c shunt motor.

Motors of different lines deviate somewhat from the curve shown because of differences in mechanical and electrical design. Also, the effect of the stabilizing field varies with individual motors as the strength of the stabilizing field can be varied only by full turns. Therefore, the relative ampere-turns produced by the stabilizing field winding vary considerably for motors of the same line. This causes variations in the droop of the speed-torque curve at high loads and in the amount of maximum break-down torque.

By far the largest number of shunt motors used on industrial applications are general-purpose, continuously rated motors such as shown in Fig. 35. The curves given in the following paragraphs apply to that type of motors. Mill type, intermittently rated shunt motors are available for particularly heavy service, and their commutating limit and maximum permissible torque are considerably higher than those of general-purpose motors. Likewise, large and special motors are often designed to meet special specifications, and their characteristics may vary considerably from those of average general-purpose motors. However, for most control applications, sufficiently accurate results may be obtained if motor performance is calculated under the assumption that the basic speed-torque curve is a straight line, at least up to normal load.

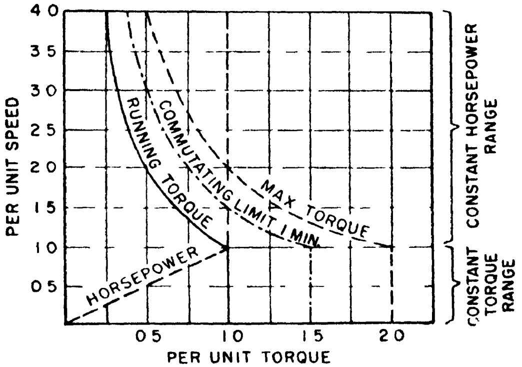


Fig. 36. Operating characteristics of general-purpose adjustable-speed d-c shunt motors

As long as a shunt motor is operated at full field, its torque is directly proportional to armature current, and the motor is capable of delivering *constant torque*. When an adjustable-speed motor operates with reduced field, the same amount of armature current produces a torque proportional to the reduced field strength. As armature current limits the rating of the motor from the heating point of view, the maximum permissible armature current limits the torque which the motor is able to deliver. As speed is inversely proportional to field strength, it follows that, at speeds above basic, the product of torque and speed which the motor is able to develop is constant. In other words, the motor operates as a *constant horsepower* machine. The *constant torque* and *constant horsepower* ranges of operation are illustrated in Fig. 36. Commutating limit and maximum torque vary with speed in the same ratio as the running torque.

In some motor designs the better cooling obtained at higher speeds is taken advantage of, when determining the rating, and a somewhat higher horsepower rating is allowed at speeds above basic. Such motors are called *variable torque* motors. Their torque above basic speed is somewhat higher than shown in Fig. 36 but falls short of being constant.

Parallel Operation

Shunt motors do not lend themselves readily to parallel operation. Figure 37 shows what happens if two motors having the same no-load speed but slightly different characteristics are mechanically connected in parallel to the same load. Both motors must run at the same speed. As a large variation in torque corresponds to a small variation in speed, the two motors take widely different shares of their load. Shunt motors are therefore not suitable for operating in parallel on the same load, unless special steps are taken to equalize the load taken by the two motors.

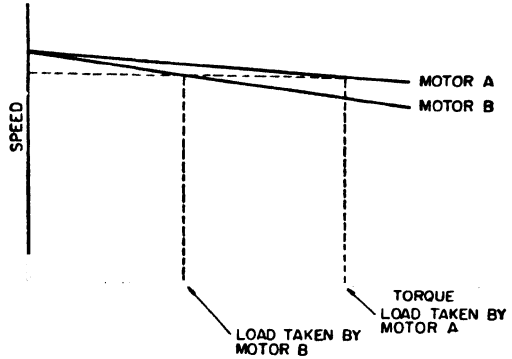


FIG. 37. Load division of two d-c shunt motors operating in parallel.

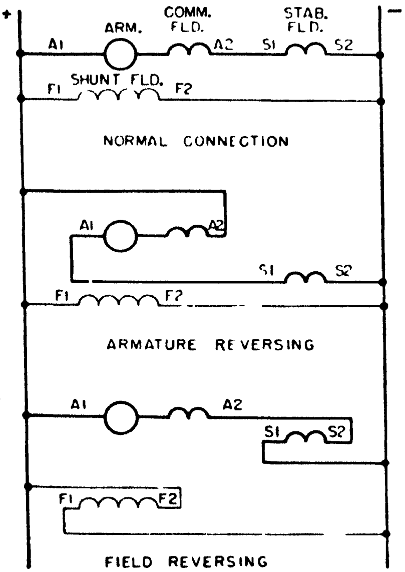


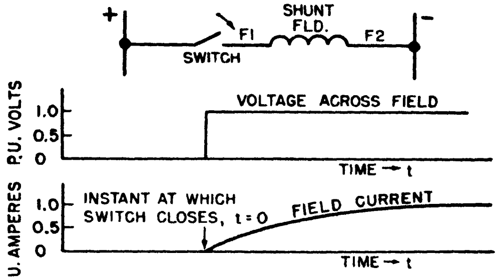
FIG. 38. Methods of reversing d-c shunt motors.

Reversing

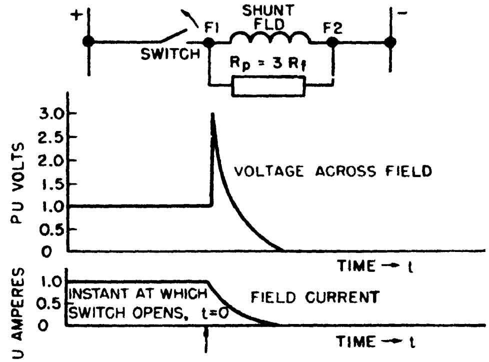
A shunt motor, like a series motor, can be reversed by reversing either its armature or its field, as is indicated in Fig. 38. If the motor is equipped with a stabilizing winding, field reversing of the motor necessitates reversing of the shunt field as well as the stabilizing field. Furthermore, switching of the shunt field, because of the high inductance of the field windings, is likely to cause high switching voltage surges and requires special precautions in the layout of the control. Because of its greater simplicity, armature reversing is used nearly exclusively on reversing controllers for shunt motors.

Field Switching

The shunt field circuit of a motor possesses a high inductance. A resistance cannot store energy, and the current through resistance



A – ENERGIZING SHUNT FIELD



B – DE-ENERGIZING SHUNT FIELD

FIG. 39. Switching of a shunt field circuit.

can be changed instantly. An inductance, however, is capable of storing energy, and such energy is stored in the flux. This energy cannot be built up or dissipated instantly; it requires a definite amount of time. If the voltage across an inductance is changed abruptly, a current transient is set up which opposes an abrupt change and causes the current to change gradually. If, through some external means, the current is changed abruptly, the energy of the flux forces an abrupt change in the voltage across the field.

Figure 39 illustrates the phenomena which occur when a shunt field circuit is switched.

Consider first the case that the shunt field is energized, which is shown in sketch *A*. At the instant at which the switch is closed, voltage V is suddenly applied to the field. This instant is zero time or $t = 0$. The steady state field current which is ultimately reached is

$$I_f = \frac{V}{R_f} \tag{29}$$ ●

where V = steady state voltage across fields in volts,
I_f = steady state field current in amperes,
R_f = shunt field resistance in ohms.

However, this amount of field current does not begin to flow abruptly at the instant the switch closes. A transient condition is set up, and the current rises from zero to its steady state value according to an exponential curve. The instantaneous value of field current versus time follows this relation:

$$i_f = I_f(1 - \epsilon^{-(R_f/L_f)t}) \tag{30}$$ ●

where i_f = instantaneous-field current in amperes,
L_f = shunt field inductance in henrys.

Exponential factor L_f/R_f, called the time constant of the field, is expressed in seconds. If the time constant of the field is known, the time required to build up field strength to 0.95 of its steady state value is three times the time constant. A field with a high inductance compared to its resistance has a higher time constant than a field with a low inductance. Generally speaking, the fields of larger motors build up more slowly than the fields of smaller motors.

The time required to build up the shunt field is of no importance to the control of continuously running drives. However, the time constant of the field becomes extremely important when control is considered for intermittent or adjustable-speed drives, when it is necessary to determine how fast the motor can possibly respond to a given control impulse.

Not only does the exponential rise of field current take place when the voltage across the field is changed from zero to a finite value but also, if the voltage is changed from one value to another, the change from one current level to the other follows the same exponential function and a time equal to three times the time constant of the field is required to change from one current level to 0.95 of the difference between current levels

Consider next the case where the field is disconnected from the power source. If it were possible to open the field circuit in zero time, the rate of change of field current would be infinity, and an infinitely high voltage would be induced in the field winding. Actually, the current cannot be interrupted in zero time because of arcing on the switch, but it can be interrupted within an extremely short time, which means that the rate of change of current and the voltage across the field winding may become very high. Oscillographic tests on field circuits of standard 250-volt shunt motors have shown that voltages of 10,000 to 20,000 volts may appear across the field terminals if the field is interrupted instantly. Such high voltages will of course lead to destruction of the field coil insulation.

High voltage peaks across the field winding can be avoided if the field current is given an opportunity to decay gradually. It can be accomplished by connecting a discharge resistor across the field winding. In sketch *B* of Fig. 39 voltage across the field winding and current are shown as a function of time, if the field is de-energized by a switch, with a discharge resistance R_p connected in parallel with the field. If current I_f flows through the field at the instant the switch is opened, the instantaneous field current decays according to the formula

$$i_f = I_f \epsilon^{-[(R_f + R_p)/L_f]t} \tag{31}$$

The instantaneous voltage v across the field, after opening of the switch, follows the function

$$v = \frac{R_p}{R_f} V \epsilon^{[(R_f + R_p)/L_f]t} \tag{32}$$

The initial voltage peak at the instant of the opening of the switch is equal to the voltage originally applied to the field, multiplied by the ratio of discharge resistance to field resistance. In the example of Fig. 39 the discharge resistance is assumed to be three times the field resistance. Thus the initial voltage peak is three times the originally applied voltage across the field. By the use of a discharge resistor, the voltage peak can be limited to a safe value.

The formulae for the build-up and decay of field current and field voltage apply generally, and the curves in Fig. 39 are plotted with the assumption that the inductance of the field is constant. This is not true in actual fact. The core of the field of d-c machines contains iron, the permeability of which is not constant. The inductance of the field varies as a function of field current, and oscillographic tests have shown that the field current during a switching operation does not follow an exponential curve.

Figure 40 is a typical current build-up curve of a d-c field, as taken from an oscillogram. The shape of the curve indicates that the inductance of the field varies greatly with changing current. If the solution of a control problem makes it necessary to know definitely the time required for building up a field to at least approximately full strength, oscillographic tests should be taken to determine the actual rate of build-up of field current. From such oscillograms an equivalent inductance can be calculated which, if it were constant, would obtain a build-up to 0.95 of ultimate field current in the same time as the actual build-up, which is three times the time constant L_f/R_f. Such an inductance can then be used with a fair degree of accuracy to calculate rise and decay of field current under varying circuit conditions.

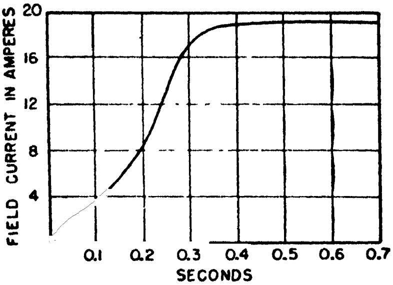


FIG. 40. Typical build-up curve of field current as taken from oscillogram.

The amount of inductance and the variation of inductance with field current do not affect the magnitude of the initial voltage peak which occurs when the field current is interrupted and a discharge resistance is used.

Armature Control

With constant field excitation on the motor, speed is proportional to generated voltage or counter emf, which is equal to the voltage applied to the armature less the voltage drop in the armature circuit. If the no-load speed is assumed to be base speed or unity, and the voltage drop is expressed in per unit of applied voltage, the full-load speed is equal to unity less armature drop. The speed of a shunt motor can be varied by inserting resistance in series with the armature. At no load, that is, at zero torque and zero armature current, external resistance does not cause any additional voltage drop, and the no-load speed remains unity. At rated torque, that is, with base armature current, the drop in per unit is numerically equal to the sum of internal and external armature resistance, expressed in per unit.

As with series motors, base resistance is defined as the ratio of base voltage to base current. Base current, strictly speaking, should be defined as full-load armature current. As the field current is only a small percentage of the full-load armature current, it is permissible to assume base current to be the rated full-load current of the motor, which includes the field current, as published in motor handbooks. When speed-torque curves are calculated and resistors are laid out, it is important to know, at least approximately, the internal armature resistance. In Fig. 41 internal resistance in per unit is plotted versus horsepower for standard, continuously rated shunt motors. The internal resistance of practical motors varies over a considerable range, and Fig. 41 gives a band, bordered by an upper and lower limit. Slow-speed motors have higher resistance than high-speed motors. Adjustable-speed motors have higher resistance than constant-speed motors.

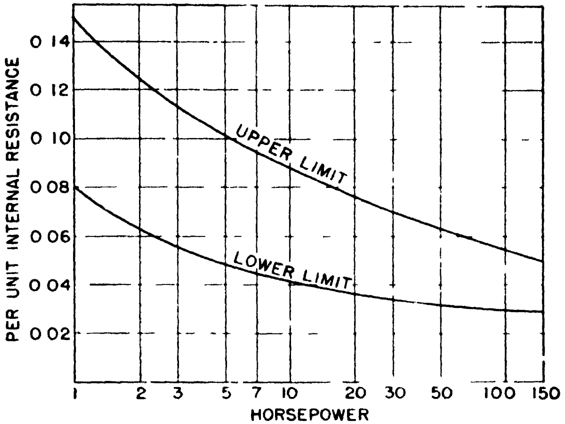


FIG. 41. Internal resistance of general-purpose continuously rated d-c shunt motors

Figure 42 indicates how the speed-torque curve for a given amount of resistance in the armature circuit can be determined. Plotting internal resistance R_{ia} and external resistance R_a on the base torque line obtains a point representing speed in per unit at base torque. A straight line through this point and the base speed-zero torque point is the curve of emf or speed, expressed in per unit versus torque. In per unit, starting torque equals $1/(R_{ia} + R_a)$, provided R_a is large enough to reduce starting torque below maximum torque. Increasing the amount of R_a decreases the speed at a given load. The reduction in speed is increased by increased load. At no load, resistance in the series with the armature has no effect on motor speed. The starting torque decreases with increasing R_a.

For the sake of simplicity, the influence of armature reaction and the effect of the stabilizing field have been neglected, and it has been assumed that the stabilizing field compensates armature reaction within the load range under consideration. Consequently, it has been assumed that factor K_T is constant, because the shunt field current remains constant. As the stabilizing field in many cases does not fully compensate armature reaction, the motor speed at full load and at higher loads may be slightly higher than the above method of calculation would indicate. However, the error thus introduced is generally not of sufficient importance to warrant the complication of considering variations in K_T with armature current.

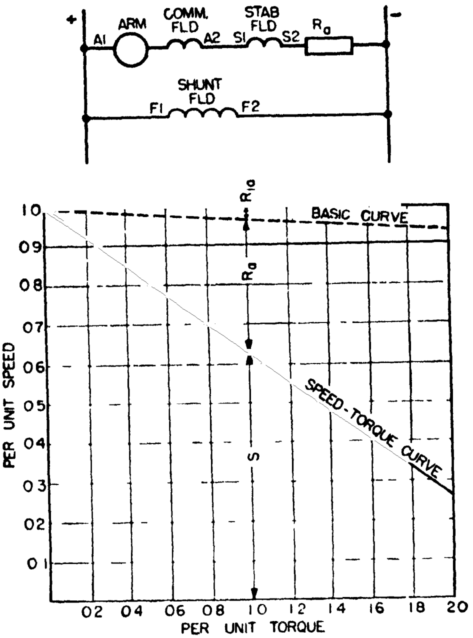


FIG. 42. Speed-torque curve of d-c shunt motor with resistance in series with the armature.

Sometimes it is desired to reduce the no-load speed below its base value. This can be done by "shunting the armature," that is, by connecting resistance both in series and in parallel with the motor armature. Such a connection is shown in Fig. 43. The following relations exist for armature current and emf:

$$I_a = I_s - \frac{V - I_s R_a}{R_p} \tag{33}$$

$$E = V - (I_s R_a + I_a R_{ia}) \tag{34}$$

With zero armature current, E becomes less than V, which means that no-load speed is reduced below base speed.

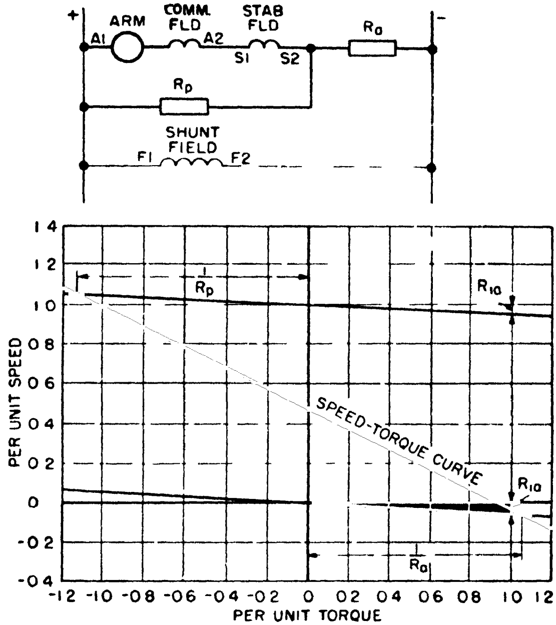


Fig. 43. Graphical method of determining speed-torque curve of d-c shunt motor with armature shunt connection

In Fig. 43 a graphical solution is given for determining speed-torque curves for various amounts of series and parallel resistance.[7] Internal resistance R_{ia} in per unit is plotted on the base torque line from the base speed point and the zero speed point. From the points thus obtained straight lines are drawn through the base speed-zero torque point and the zero speed-zero torque point, respectively. From the zero torque line, $1/R_p$ is plotted to the left and $1/R_a$ to the right, where they intersect with the above-mentioned straight lines. A straight line through these points of intersection is the speed-torque curve. The graphical solution can also be used to determine the amount of series and parallel resistance necessary to obtain a desired speed-torque characteristic.

Speed-torque curves for shunted armature connection are less steep than for straight series resistance connection. A lesser amount of speed change corresponds to a given amount of torque change. With series resistance R_a held constant, the no-load speed decreases as the amount of parallel resistance R_p is decreased. Changes in R_p have little influence on the starting torque, which is largely governed by R_a. With parallel resistance R_p held constant, increasing R_a decreases the no-load speed and the starting torque.

Speeds below base speed are obtained in the negative torque quadrant 2. A considerable amount of braking torque developed by the motor when its armature is shunted can be utilized for slowing down the motor quickly. It is possible also to obtain speeds below basic speed if the load on the motor is overhauling.

Dynamic Braking

When the motor field is connected across the line and the armature short-circuited through a resistance, and the motor is then driven by an overhauling load, it acts as a shunt generator feeding current into the resistance. This operating condition is the same as shown in Fig. 23. Dynamic braking is used quite frequently to bring a motor to a quick stop.

Field Weakening

As the speed of a d-c motor is inversely proportional to the effective flux, the speed of a shunt motor can be increased by weakening its shunt field current. It is done by inserting resistance in series with the shunt field. As the design of the field structure of motors of various sizes and the saturation of different motor fields vary considerably, there is no general formula for determining the effective field strength and the speed for partial field currents. Figure 44 gives the relation of no-load speed as a function of field current for a typical shunt motor. Speed is expressed in per unit of base speed, and field current is expressed in per unit of full-field current. The speed-field current curve applies to a specific motor. It is indicative of the general shape of the curves to be expected, but it is not sufficiently general to permit the use of the curve as a basis of calculating the performance of other shunt motors.

In order to predict motor performance under weakened field condition, it is necessary to obtain from the motor designer a curve giving no-load speed as a function of field current. With a given no-load speed, as determined by the desired performance of the drive, the complete speed-torque curve of the motor can be determined as follows. Since torque varies directly and speed inversely with flux, base armature current produces a torque which, on a per unit basis, is inversely proportional to no-load speed. If the stabilizing winding fully neutralizes armature reaction, base current flowing through the armature causes an armature voltage drop and a per unit drop in speed between no load and full load, which is the same as under full-field condition. For instance, if no-load speed under weakened field conditions is twice base speed, the same drop in speed which would occur at full load with full field occurs at one half base torque. The speed-torque curve between no load and full load is a straight line, as armature current and armature drop are proportional to torque. Commutation limit and maximum permissible torque vary inversely proportional to no-load speed.

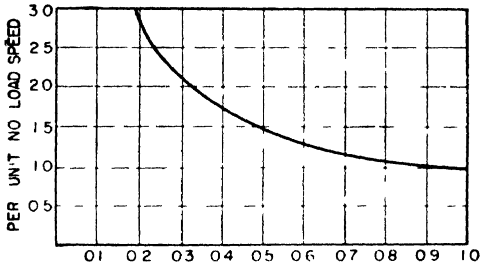


Fig. 44. Typical d-c shunt motor curve showing variation of speed with field current.

In Fig. 45 typical speed-torque curves are plotted for a four-to-one adjustable-speed shunt motor with field control. Speed is expressed in per unit of base speed, and torque is expressed in per unit of full-load torque at base speed. At higher speeds, regulation becomes poorer, and a given torque change causes a greater variation in speed than at lower speeds. The maximum breakdown torque of the motor is inversely proportional to no-load speed. A motor with a maximum torque of 2.4 at full field develops only a maximum torque of 0.6 at a no-load speed of 4. In order to obtain a reasonably high starting torque, controllers for adjustable-speed shunt motors should make provision for starting the motor with full field. The foregoing statements are based on the assumption that armature reaction is fully compensated by the stabilizing field. Actual motor performance curves may deviate somewhat from the ones shown in Fig. 45, as in many motors the design of the stabilizing field is a compromise.

If the field circuit of a shunt motor is interrupted so that no field current flows, the effective flux is not reduced to zero but a small residual flux remains. With the armature circuit connected to the line and the motor driving a low-friction load, for instance a motor generator set, the residual flux may enable the motor to develop sufficient torque to overcome the load torque and the motor may attain a very high speed. Therefore, controllers for shunt motors, which are likely to be lightly loaded or even overhauled, should make provision to prevent energizing the armature circuit in case of loss of field current.

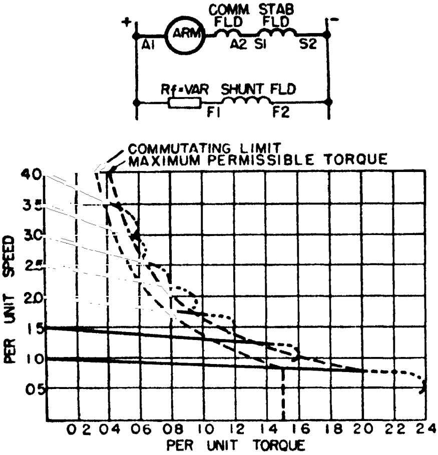


Fig. 45. Typical speed-torque curves of adjustable-speed d-c shunt motor with field control.

COMPOUND MOTORS

Compound motors are equipped with both shunt and series fields. The shunt field supplies a flux substantially constant and independent of load, as in shunt motors. The series field supplies a flux which varies with load, as in series motors. Speed-torque characteristics are a cross between those of shunt and series motors, their shape depending on the relative amount of shunt and series field.

In Fig. 46 typical speed-torque curves are plotted for compound motors. Curve A applies to a motor in which the series field is predominant. It closely resembles the curve for a series motor, except that the no-load speed is limited to a definite value. Motors with such a characteristic have the advantage of a high starting torque and the drooping speed characteristic, associated with the series motor, and they can be used in cases where the motor may be completely unloaded without danger of a run-away. Curve *B* belongs to a motor in which, at full load, shunt and series field are of equal strength. The curve is flatter than curve *A*, but it still possesses an appreciable droop, and the motor develops a higher starting torque than a shunt motor, although less starting torque than a series motor. Curve *C* pertains to a motor in which the shunt field is predominant. The curve is slightly more drooping than that of a straight shunt motor, which makes the motor better suited for loads that change suddenly. This increased droop obtains better division of load if motors are operated in parallel.

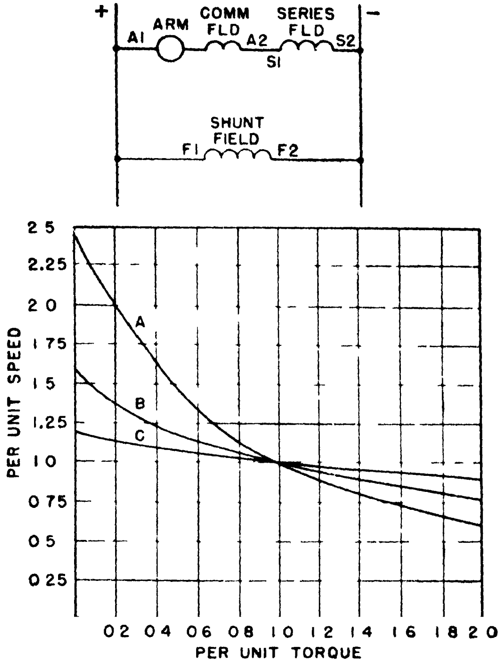


FIG. 46 Speed-torque curves of d-c compound motors. Curve *A*: Series field predominant. Curve *B*: Series and shunt field equal. Curve *C*: Shunt field predominant

Compound motors are reversed by reversing either the armature or both shunt and series fields. Armature reversing is preferred because control connections are simpler. If the shunt field can be opened by the controller, a discharge path must be provided. The speed-torque characteristics of compound motors can be varied by inserting resistance both in the shunt field and in the armature circuit. Thus speed control is possible by the same type of circuits described for series and shunt motors. Speed-torque curves can be calculated by the same methods explained for series motors. It is necessary to determine a curve for K_T as a function of field current from the motor characteristic curves. Calculating field and armature currents and armature drop from the circuit constants yields E, and thus torque and speed can be obtained with the help of K_T.

ADJUSTABLE-VOLTAGE SYSTEMS

Since the speed of a shunt motor is proportional to its electromotive force, which is equal to voltage applied to its armature less the voltage drop in the armature circuit, the speed of a shunt motor can be varied by varying the voltage impressed on the armature. Speed control based on this principle is called adjustable-voltage control or, after its inventor, Ward Leonard Control. For this system of control it is necessary to provide a source of adjustable-voltage direct current, which is most conveniently obtained from an individual d-c generator, usually of the shunt or compound wound type. The d-c generator is provided for the sole purpose of supplying power to its associated d-c motor. It is driven either by an electric motor or a prime mover.

Although the cost of an adjustable-voltage system is considerably higher than the cost of a conventional shunt motor, because of the separate generator set with its starting equipment, it is one of the most widely used systems of control wherever exacting service requirements are to be met or when large d-c motors are to be controlled. Its principal advantages are:

1. Speed control of the motor is obtained by adjusting generator voltage by field control, which eliminates the use of heavy contactors in the armature circuit.
2. The motor can be reversed by reversing the polarity of generator voltage through reversal of the generator field current. This eliminates heavy armature reversing contactors.
3. Greater range of speed control can be obtained than with a straight shunt motor. The regulation at reduced speeds is far better than with series resistance in the armature circuit.

4. The power handled in the control of the generator field is roughly 1 per cent of the total power of the drive. It is therefore easy to provide a large number of control steps, which is conducive to smooth control.
5. By using generators of special design or by exciting the generator field with exciters of special design, it is possible to adapt the speed-torque characteristics of adjustable-voltage systems to specific service requirements.

Conventional Shunt Generator Control

Using a straight shunt generator in conjunction with a shunt motor, excited with constant field strength, obtains speed-torque characteristics which are straight lines. The droop between no-load and full-load speeds is proportional to the drop in the armature circuit of the two machines. Thus the regulation between no load and full load is independent of no-load speed and constant over the whole speed range. As the motor field strength is kept constant, torque is solely a function of armature current. Therefore, within the range of armature voltage control, the adjustable-voltage system is a constant torque system, and the delivered horsepower is proportional to the speed.

With conventional machines, stable operation can be obtained for a speed range down to 0.1 of basic motor speed, and a speed range of 10 to 1 is considered the widest range obtainable, unless specially designed machines are used. It is possible to increase this speed range by another 4-to-1 ratio by weakening the motor field, while keeping the armature voltage at its rated value. Thus a total speed control range of 40 to 1 can be obtained. With the motor field weakened, the system is no longer able to develop constant torque, but it becomes a constant horsepower system. Base speed is the no-load speed with full motor field and full armature voltage. Figure 36 describes also the operating range of this system. The speed-torque curves of Fig. 45 apply to an adjustable-voltage system in the motor field weakening range.

Figure 47 shows in an elementary manner the principal circuits of an adjustable-voltage system with a shunt generator. The motor generator set consists of a driving motor, a generator, and an exciter, if no other source of d-c power for field excitation is available. In order to increase the accuracy of speed control by maintaining a constant exciter bus, the exciter may be flat compounded or it may be equipped with a voltage regulator. The d-c generator field is connected to the exciter bus through an adjustable resistor or rheostat, by means of which the motor shunt field current and the generator voltage can be varied. On equipments with a wide speed range, the field rheostat may be built as a potentiometer to obtain better field control in the range of low generator voltages. Reversal of generator polarity, which corresponds to reversal of the direction of rotation of the d-c motor, is obtained by reversing the polarity of the generator field leads, as indicated by broken lines.

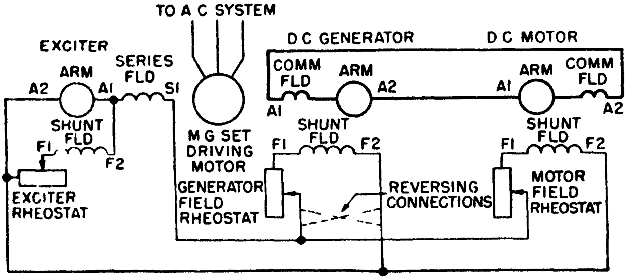


FIG. 47. Principal connections of adjustable-voltage system with shunt generator.

The d-c motor shunt field is connected to the exciter bus. If the d-c motor operates with armature voltage control only, the motor field is connected to the exciter bus directly or through a fixed resistance. If speed control by motor field weakening is desired, an adjustable resistor or rheostat is connected in series with the motor field. The controller should be designed so that, during starting and speed control by armature voltage, full field is maintained on the

FIG. 48. Two motor generator sets for two adjustable-voltage mine hoist drives

motor in order to take advantage of the maximum starting torque available.

The heavy power circuit between the armatures of d-c generator and d-c motor is called the loop circuit. No control devices are necessary in this circuit to obtain speed control. A circuit breaker or line contactor is often used in the loop circuit to obtain overload protection in the d-c power circuit or for reasons of control sequence and interlocking. Shown in Fig. 48 are two motor generator sets, used for adjustable-voltage control of two mine hoists.

Neutralizing

When the generator shunt field is disconnected from the exciter bus, the field current drops to zero. The generator voltage, however, will not drop to zero because of the residual magnetism in the generator field structure. As the resistance of the generator and motor armature loop is very low, a very low generator voltage causes a heavy current to flow through the loop circuit. This enables the d-c motor to develop a substantial torque, and it may creep at a very low speed.

This can be prevented by using a generator field connection, which is called neutralizing or "suiciding." In Fig. 49 a double-throw switch is indicated in the shunt field circuit. With the switch blades down, current flows through the field in the direction of the solid arrow, which obtains polarity on the generator armature as indicated. When it is desired to stop the drive, the switch blades are thrown up, thus disconnecting the field from the exciter bus and connecting it to the generator armature in such a manner that the polarity of the field is reversed and field current flows in the direction of the broken arrow. This field reversal "kills" the residual magnetism, that is, it reduces the generator flux practically to zero, which in turn brings the generator voltage to zero and causes the d-c motor to remain at standstill. Once the residual magnetism is brought to zero, the flux cannot build up in the opposite direction, and the neutralizing connection may remain established until the motor is started up again by connecting the generator shunt field to the exciter bus.

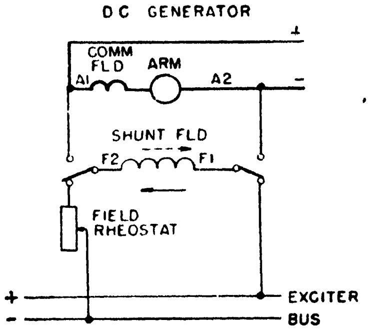


Fig. 49. Neutralizing of d-c generator shunt field.

To avoid heavy circulating current in the loop circuit because the motor pumps back into the generator, if the generator voltage is forced to zero with the d-c motor still at a substantial speed, the generator voltage should be reduced gradually, and the neutralizing connection should be established only after the generator voltage has dropped to a reasonably low value. When an adjustable-voltage equipment is placed in service, it is very essential to give the neutralizing connection a careful check to see that polarities are correct. If the polarity of the neutralizing connection is reversed, the generator builds up voltage as a self-excited generator to a dangerously high value.

Dynamic Braking

When an adjustable-voltage drive is decelerated and stopped, it is not necessary, or even desirable, to open the loop circuit between motor and generator. Leaving the loop circuit established and reducing the generator voltage by means of field control to zero obtain smooth retardation of the drive to standstill without the necessity of providing any special braking circuit. If the generator voltage is lower than the motor emf, the motor develops a negative torque

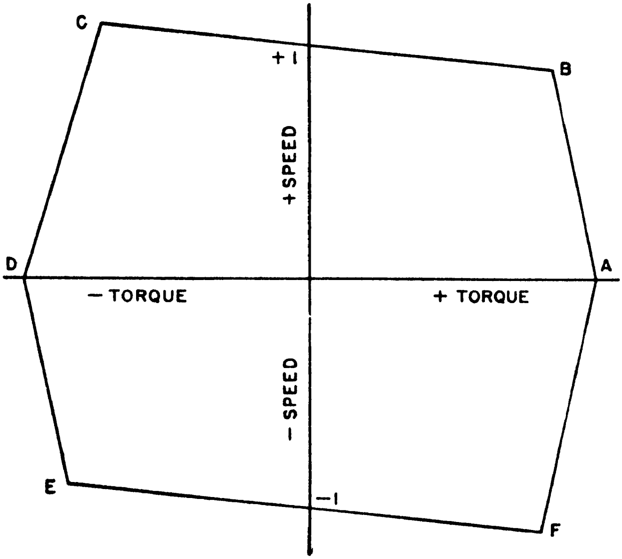


FIG. 50. Envelope of performance range of an adjustable-voltage drive with shunt generator.

which can be used to retard an overhauling load with exactly the same connections as used to drive a positive load.

The torque which an adjustable-voltage drive is able to deliver is proportional to armature current. The maximum torque of the drive is determined by the amount of current the d-c machines are able to commutate. In Fig. 50 the envelope is given which circumscribes the performance range of an adjustable-voltage drive with shunt generator. At standstill, a starting torque is developed determined by point *A* and limited by the ability to commutate. As voltage is increased and the drive accelerates, the maximum available accelerating torque varies along line *A–B*. Point *B* corresponds to a smaller torque as, with increased voltage, the armature current which can be commutated decreases. When the voltage is raised to its rated value, the drive operates at a speed determined by line *B–C*, depending on the amount of driving or retarding torque required of the motor. When the voltage is reduced to retard the drive, the maximum retarding torque available is given by line *C–D*. When the generator field excitation is reversed, the available starting torque corresponds to point *D*, which is given by the commutating limit. Accelerating torque is determined by line *D–E*, and retarding torque by line *F–A*. For a specific drive, the performance limits can be determined from the commutation limits of the d-c machines. Both generator and motor must be considered as either of the two machines may be the one that determines the commutating limit.

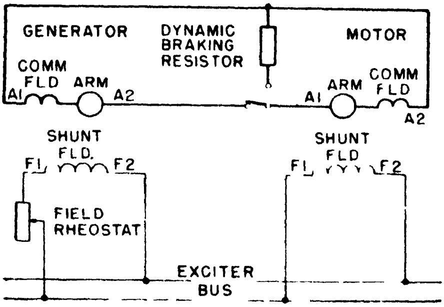


FIG. 51. Emergency dynamic braking connection.

When a circuit breaker contactor is provided in the loop circuit, the armature of the motor may be disconnected from the generator in case of overload or some other emergency. To retard the motor rapidly, an emergency dynamic braking circuit may be employed which in its simplest form is illustrated by Fig. 51. A switch is indicated in the loop circuit. With the switch blade down, the loop circuit is closed. With the switch blade up, the motor armature is disconnected from the generator and short-circuited through a dynamic braking resistor. The motor circuit is then the same as shown in Fig. 22, and the same kind of speed-torque curves are obtained.

Again, the commutating limit of the motor determines the minimum permissible amount of dynamic braking resistance, that is to say, the largest amount of dynamic braking torque which the motor may deliver at full speed. As the motor decelerates, the available dynamic braking torque decreases. When rapid deceleration is desired, the amount of dynamic braking resistance may be reduced in steps as the motor speed is reduced.

Control of Rate of Acceleration and Deceleration

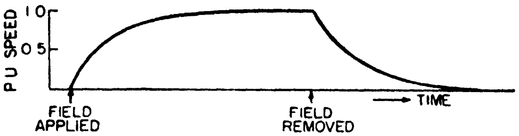
Rate of acceleration is governed by the rate at which the generator voltage builds up from zero to its rated value. Likewise, rate of deceleration is determined by the rate at which generator voltage is reduced from its full value to zero. By proper design of generator field control circuits and proper selection of the rate at which the generator field current is increased or decreased, the rate of acceleration and deceleration may be selected to suit the particular requirements of the driven machinery. There is one limitation, and that is the fastest rate of build-up and decay of generator voltage which can be obtained when full field is suddenly applied or removed.

Because of inductance of the generator field and armature structure, voltage builds up to its full value as an exponential function of time, if full-field excitation is suddenly applied. Likewise, when the field circuit is opened, generator voltage decays according to an exponential curve. As in the case of shunt motor fields, a discharge path must be provided when the generator field is opened.

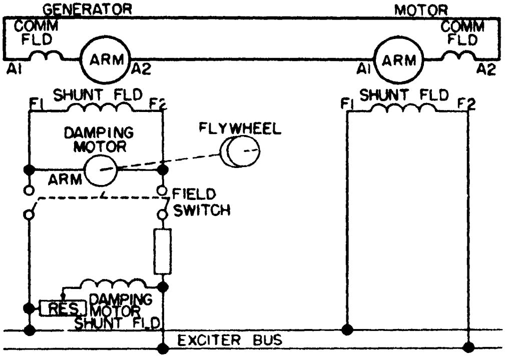
In Fig. 52 curve *A* shows the speed of an adjustable-voltage drive plotted versus time, when full generator field is suddenly applied or removed. Acceleration and deceleration are not at all uniform. Initially, the rate of change of speed is high, and it varies during the time of acceleration and deceleration. This is very objectionable for certain drives, such as elevators. It is much more desirable to have a uniform rate of acceleration and deceleration.

Diagram *B* shows a control system which accomplishes this purpose. A small "damping motor" is provided, which is coupled to a flywheel to increase the inertia of its armature. The damping motor field is excited at a constant rate from the exciter bus. The motor armature is connected in parallel with the generator shunt field.

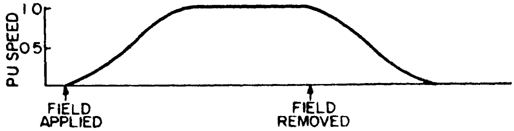
When the generator shunt field circuit is closed, the damping motor is at standstill. Its armature resistance is low, and a large portion of the generator field current is shunted through the damping motor, which starts and accelerates the flywheel. As the speed of the damping motor increases, its counter emf causes the current through its armature to decrease, and a correspondingly increased amount of current flows through the generator field. When the damping motor reaches full speed, full current flows through the generator shunt field. Thus the damping motor has the same effect as if a large capacitance were connected in multiple with the generator shunt field.



A-BUILD-UP AND DECAY OF SPEED WITHOUT DAMPING MOTOR



B-CONNECTIONS OF DAMPING MOTOR IN GENERATOR FIELD CIRCUIT



C-BUILD-UP AND DECAY OF SPEED WITH DAMPING MOTOR

FIG. 52. Effect of damping motor on acceleration and deceleration.

When the generator shunt field circuit is opened, the flywheel overhauls the damping motor and causes it to act as a generator, which maintains voltage across the generator field terminals. As the flywheel loses speed, the emf of the damping motor decreases, which in turn decreases the field current. Thus, by proper selection of the flywheel effect of the damping motor and proper adjustment of the damping motor shunt field, the rate of acceleration and deceleration of the adjustable-voltage drive can be adjusted. Curve *C* shows speed plotted versus time for a drive with damping motor, and the effect of the damping motor can be seen by comparing curve *C'* with curve *A*. The rate of acceleration and deceleration is more uniform.

Compensation of Regulation

On many adjustable-voltage equipments, for instance for elevators, it is necessary to obtain a constant speed on each controller point, regardless of the load on the motor. Means must then be employed to compensate for the natural speed regulation due to the drop in the loop circuit, which is a function of torque or armature current. One way to compensate for the armature drop is to add a series field to the generator, making it a flat compounded machine. As the armature current increases, the series field boosts the generator voltage and reduces the amount of voltage change between no load and full load.

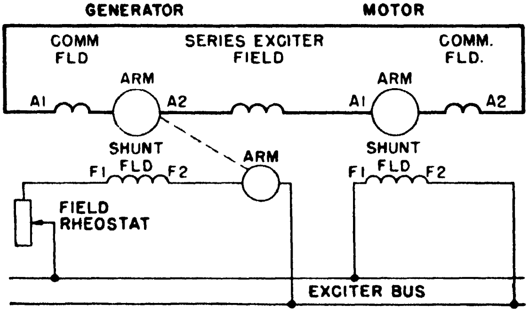


Fig. 53. Adjustable-voltage system with series exciter

Another way to compensate regulation is to use a series exciter, as shown in Fig. 53. A small exciter is coupled to the shaft of the generator. Its field is connected in series with the loop circuit. Its armature is connected in series with the generator shunt field. Thus, as the load and the loop circuit current increase, the series exciter increases the voltage across the shunt field and thereby the shunt field current. Likewise, when the motor is overhauled and the current in the loop circuit reverses, the series exciter reduces the generator shunt field current and compensates for the rise in speed under the influence of overhauling loads.

The circuits described above are based on the principle that the control reacts to armature current and uses it to compensate for speed regulation. Although results obtained are satisfactory for many applications, accurate speed control cannot be obtained, as the internal characteristics of d-c machines, especially their saturation, vary over their operating range. If perfect compensation of regulation is attained at one speed, compensation is imperfect at other speeds. Perfect maintenance of speed over the whole operating range can be obtained only if the control reacts to the actual speed of the motor and corrects for speed variations through closed cycle controls, discussed later in this chapter.

Three-Field Generators [5]

On certain applications it is desired not so much to obtain close control of speed between no load and full load but to control the

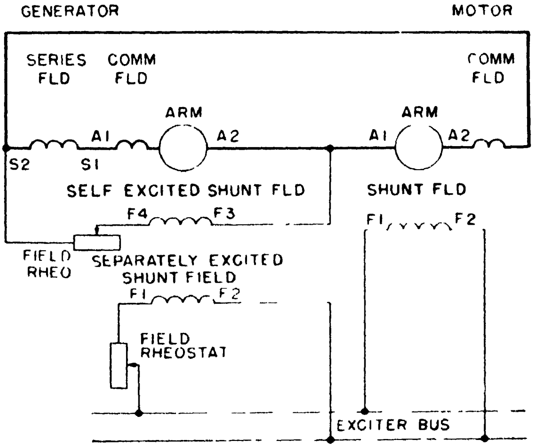


FIG. 54. Adjustable-voltage system with three-field generator.

amount of torque the system is able to develop. A typical application is the electric shovel. The three-field generator has a load-limiting characteristic. In Fig. 54 the connections of a three-field generator are indicated. As the name implies, it is equipped with three field windings on a common magnetic structure. A differential series field is connected in series with the armature in such a sense that, with rising armature current, the series field reduces the generator voltage. A self-excited shunt field is connected across the generator terminals. A separately excited shunt field is connected to the constant exciter bus.

Figure 55 shows the volt-ampere characteristics which can be obtained with three-field generators. The curves are drawn for varying percentages of flux contributed by the individual field windings. For a given total shunt field excitation the no-load voltage is the same, regardless of the relative amount of self-excited and separately excited fields. By proper selection of the total field strength, the maximum current which the generator can produce under stalled motor condition can be limited to a definite value, thus making the three-field generator self-protecting against overloads.

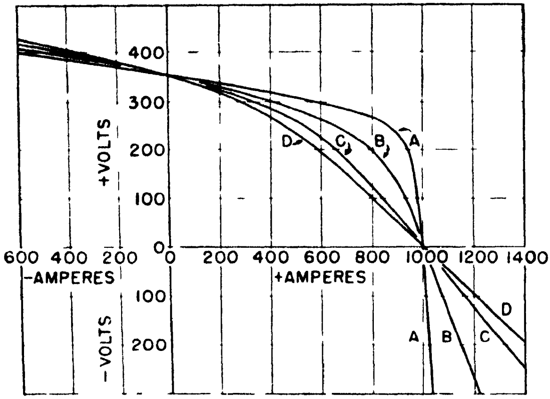


FIG. 55. Voltage versus current characteristic of a three-field generator for varying percentages of the three fields.

Curve	Separately Excited Shunt Field, %	Self-Excited Shunt Field, %	Differential Series Field, %
A	20	80	10
B	40	60	30
C	60	40	50
D	100	0	90

The shape of the volt versus ampere curve can be varied by changing the relative amounts of the separately and self-excited shunt fields. If an almost constant current from zero voltage to maximum voltage is desired, a greater percentage of self-excited shunt field is used. Once the inherent characteristics of a generator are chosen, its performance can be varied by varying the amount of separately and self-excited shunt field current, by changing resistance in series with the field windings. It is impractical to control the series field because high current is involved in that field circuit.

Since voltage corresponds to speed and armature current to torque, the volt-ampere characteristics of the generator can be readily translated into speed-torque characteristics of the drive. In Fig. 56 the speed-torque curves of a typical three-field generator system are plotted when only the strength and the direction of the separately excited shunt field are varied. Reducing the amount of field strength reduces the amount of stalled torque. Reversing the separately excited shunt field reverses the drive. The curves are plotted in all four quadrants of possible motor operation. Stable motor performance can be obtained both with the motor driving the load and with the motor being overhauled by the load.

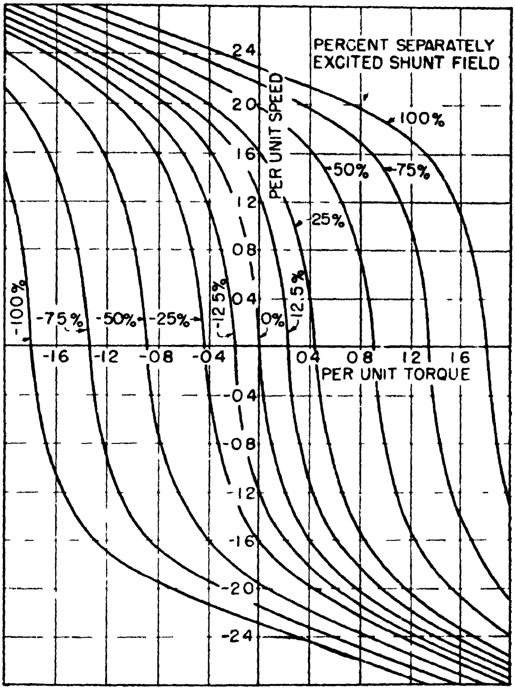


Fig. 56. Speed-torque curves of three-field generator system with varying separately excited shunt field.

In Fig. 57 the effect of varying the self-excited shunt field in strength and direction is shown. Reversing the self-excited shunt field affects the no-load speed but does not reverse the drive.

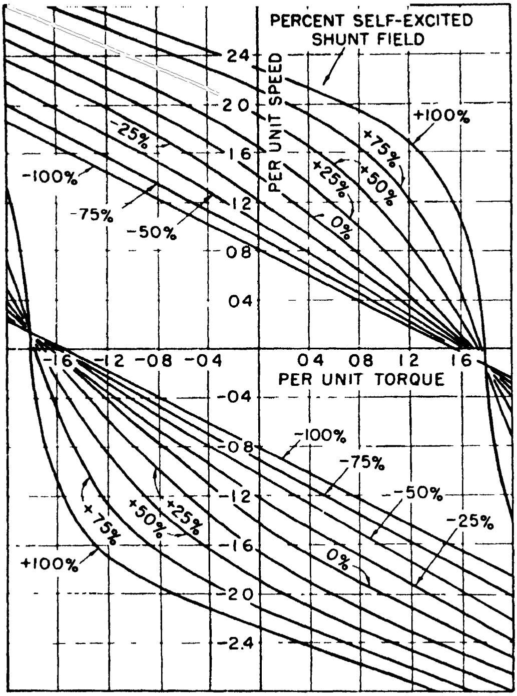


FIG. 57. Speed-torque curves of three-field generator system with varying self-excited shunt field.

Closed Cycle Control

The methods of controlling the speed-torque characteristics of a motor discussed so far make use of the inherent characteristics of the machine. After selecting a motor with general characteristics most suited to a particular drive, the designing engineer selects a type of control which obtains speed-torque curves that match, as closely as possible, the ideal speed-torque curves which would obtain most efficient performance of the drive. Once a control system has been laid out, possibly with auxiliary rotating apparatus, and certain control connections have been established, each portion of the overall system performs in accordance with its inherent characteristics. For instance, speed variations due to the drop in the loop circuit of an adjustable-voltage system may be reduced by the use of a series exciter, but there is no assurance that speed, or even generator voltage, will be maintained accurately under all load conditions because the control has no means to "see" speed or generator voltage and to regulate the system accordingly.

If it is desired to adjust and to maintain a certain characteristic quantity of a drive, for instance its speed, over a wide range of load conditions, a closed cycle controller may be used. In a closed cycle control system a quantity representing a certain output value is measured and compared to a standard representing the desired performance. Any deviation from the standard is fed back into the control system in such a sense that it will reduce the deviation from the standard. Thus the control system functions not only as a controller but also as a regulator.

Adjustable-voltage systems are especially suited for closed cycle control because the amount of energy which has to be controlled in the fields of the d-c machines is only a small fraction of the total output of the system. The d-c generator can be regarded as a crude power amplifier. One kw input to its field circuit controls approximately 100 kw output at the machine terminals. The accuracy of the amplifier is limited by the inherent regulation of the generator and its response is limited by the time required to effect a change in generator voltage following a change in the voltage applied to the generator field terminals.

On large adjustable-voltage systems, the amount of energy required to control the generator field is quite sizable. In a closed cycle control system the amount of energy used to measure the deviation of performance from the standard must be so small that the energy taken out of the system for control purposes has no effect on the system performance. As the speed of response of the whole system is determined by the sum total of the time constants of the various mechanical and electrical elements of the system, it is desirable to keep the energy stored in the control elements of a closed cycle system as low as possible in order to obtain fast response to deviations from the standard of performance.

Special exciters are used to excite the generator fields, and control of the output of a system is obtained by controlling the field of the exciter. Using exciters of special design, a high rate of amplification can be obtained between the incoming control signal and the output of the exciter, which in turn determines the output of the adjustable-voltage system.

As an example, consider a system in which it is desired to maintain speed accurately at any set value, regardless of load. As a standard, a potentiometer can be connected across a regulated constant-voltage d-c bus. On that potentiometer, any desired amount of voltage can be tapped off and fed into the field circuit of the exciter. The exciter produces a certain voltage, which is impressed on the generator field, which in turn produces a certain no-load speed of the motor. The actual speed of the motor is then measured by a tachometer generator, the output voltage of which is balanced against the standard so that the net field strength of the exciter is determined by the difference between the standard and the tachometer voltage signal. If the actual speed of the motor deviates from the speed corresponding to the standard, the change in tachometer output introduces a change in the excitation of the exciter, which reduces the deviation of the actual speed of the system from the desired speed. Adjustment of the system to operate at different speeds is obtained by varying the standard, for instance by building the potentiometer in the form of a rheostat. In a similar manner, other output quantities can be controlled. Generator voltage can be held constant by comparing the generator voltage directly with the standard. Torque can be controlled by measuring the loop circuit current by the voltage drop across some resistance in the loop circuit, and the drop balanced against a standard. Load division between generators operating in parallel can be controlled by balancing the armature currents of several machines against each other, to mention a few of the more commonly used closed cycle control applications.

The total time of response of an adjustable-voltage control system is governed by the time lag in the response of the exciter and generator fields and the inertia of the drive, which must be accelerated and decelerated. To keep the time of response at a minimum, the time constant of the exciter must be made as small as possible, introducing the hazard of hunting. When a closed cycle control system is designed, careful consideration should be given to the stability problem, and means should be provided to anti-hunt the system. Hunting is one of the most involved phenomena confronting an engineer, and so far no simple analytical method has been devised to determine definitely whether or not a given system will hunt.

It can be stated in general terms that a closed cycle control system can be anti-hunted by providing components in the control circuit which do not have any effect during steady state operation but tend to slow down the response of the system should a rapid change take place in the operating condition of the system. The most reliable method to solve the anti-hunt problem is to conduct tests on typical installations to determine the factors affecting stability, and then provide sufficient flexibility in the circuit design to permit adjustment of the anti-hunt features at the installation. Typical anti-hunt circuits are discussed in Chapter 13.

Regulating Exciters[9, 10, 11]

Regulating exciters do not differ in principle from conventional d-c exciters. To make them respond fast to changes in field excitation, their field structure is laminated. To obtain linear response of their output voltage to changes in field current, their magnetic design is such that, when used within their rating, they operate on the unsaturated or straight-line portion of their magnetizing curve. When used in closed cycle control circuits, regulating exciters are equipped with a multiplicity of fields, each responding to a particular control signal. The sum total of the flux set up by the various fields determines the output voltage of the exciter, and thus the field current of the main generator. Numerous control systems have been developed to obtain performance suitable for specific drives. Many of them are based on the principle of establishing a standard which is used to provide a fixed excitation of one of the exciter fields. Against this standard is balanced the excitation of one or more other control fields, which are excited by voltages measuring the actual performance of the drive. Regulating exciters built by the Allis-Chalmers Manufacturing Company are marketed under the name of Regulex; those of Westinghouse Electric Corporation are called Rototrol. Principal connections of a control system using a regulating exciter are shown in Fig. 58. The shunt field of the generator is connected to the armature of the exciter. In series with the generator shunt field is connected a self-excited exciter shunt field so proportioned that it will sustain, but not build up, exciter armature voltage. The rest of the exciter field structure consists of three separately excited shunt fields, wound on the same poles with the self-excited field. The control field is connected to the constant exciter bus through the field rheostat. This field is the standard, and the magnitude of its flux determines the speed at which it is desired to operate the drive. The second field is the voltage-regulating field. It is connected across the generator terminals, and its field current is proportional to the terminal voltage of the generator. The third field is the load-regulating field, and it is connected across the interpole field winding of the generator. The current of the load-regulating field is proportional to the drop across the interpoles, which means that it is proportional to armature current or load.

The two regulating fields are so connected that they oppose each other. Thus the net excitation of the regulating fields is proportional o generator voltage minus loop circuit drop, that is to say, the net xcitation of the regulating fields is proportional to the actual speed of the drive. The control field and the regulating fields are so proportioned that, when the drive operates at the desired speed, the control field and the regulating fields cancel each other.

When excitation is applied to the control field, the exciter voltage builds up and, correspondingly, the generator voltage builds up, until the regulating fields cancel out the control field. When this point is reached, the self-excited field sustains the exciter voltage, and the drive operates at a speed corresponding to the excitation of the control field. If the speed changes with load changes, the net excitation of the regulating fields no longer cancels the control field excitation. As a result, there is a net surplus of excitation to raise or lower the exciter voltage until a balance is struck and the net excitation of the regulating fields again cancels the control field excitation. This means that the speed has been readjusted to its original value, and the exciter voltage is again sustained by the self-excited shunt field.

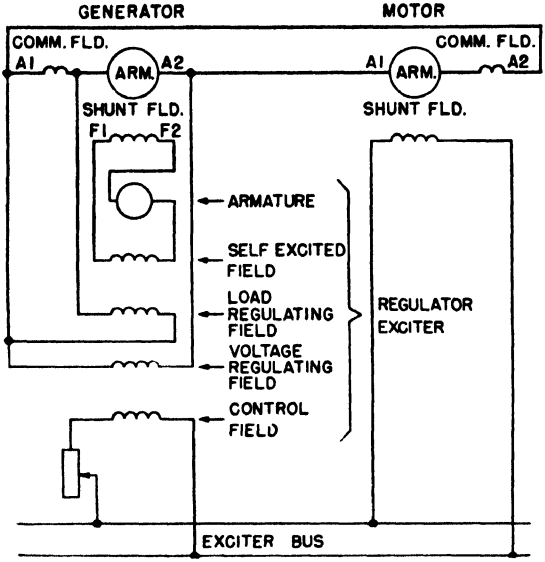


FIG. 58. Speed control with regulating exciter.

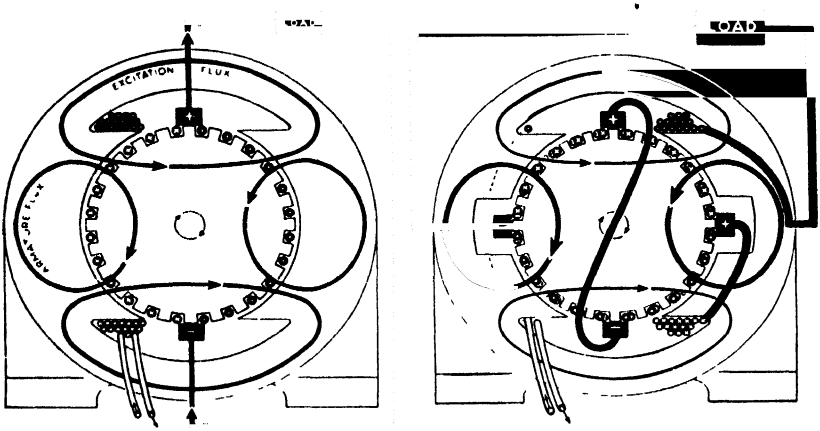
Amplidyne Exciters [12, 13, 14, 15]

The amplidyne is a regulating exciter with a high rate of amplification between the power required to excite its fields and the output taken from its armature. In outward appearance it does not differ from any conventional d-c exciter. It possesses the same essential elements as an ordinary small d-c generator, namely, a field structure, an armature with commutator, and a set of brushes. Shown in Fig. 59 is a group of amplidyne exciter sets, each amplidyne being driven by an induction motor. Peculiar characteristics make the amplidyne a particularly valuable tool for use in closed cycle control systems.

FIG. 59. Group of four amplidyne exciter sets.

Consider first the basic functions of a conventional d-c exciter. In Fig. 60 sketch *A* shows in diagrammatic form the magnetic and electric circuits of a conventional d-c generator. The excitation of the shunt field sets up a flux which, in combination with the energy transmitted mechanically to the armature, generates electric energy. This energy is taken out of the armature through a set of brushes between the field poles. On an average, 100 watt input into the shunt field controls 10 kw output at the machine terminals, a ratio of 100 to 1.

The load current flowing through the armature sets up a flux in quadrature with the shunt field flux. Armature flux or armature reaction in conventional d-c machines is considered a detriment rather than an asset. In the amplidyne this armature flux is put to work, as indicated in sketch *B* of Fig. 60. The brushes between the field poles are short-circuited, and current flowing through this set of brushes is used solely to set up an armature flux. If it is assumed



A. Conventional d-c generator. *B*. Amplidyne.

FIG. 60. Diagrammatic sketch of magnetic and electric circuits of conventional d-c generator and amplidyne.

that 100 watts are required to produce this flux, 1 watt in the shunt field winding suffices to control the armature flux.

A second set of brushes is located under the shunt field poles, and the load circuit, connected to this second set of brushes, utilizes the

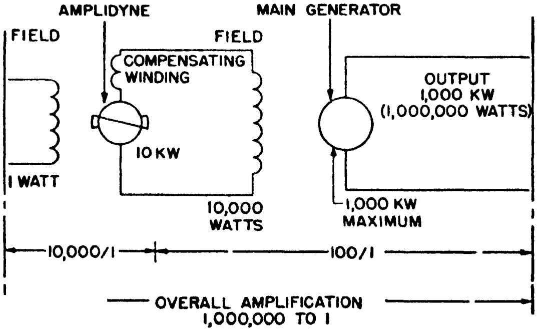


FIG. 61. Amplification factor of an adjustable-voltage control system with amplidyne exciter.

energy generated by the intersection of the armature conductors with the armature flux. A compensating winding is arranged on the field poles and connected in series with the load current. This compensating winding suppresses armature reaction due to the load current so that the amplidyne output voltage is proportional to its net field excitation and not affected by armature reaction due to load current.

One watt input into the shunt field controls 100 watts in the armature circuit, setting up the armature flux because of the short-circuited brushes. These 100 watts in turn can be used to control 10 kw in the load circuit. The amplidyne is in fact a two-stage amplifier in which 1 watt input into the field controls 10 kw output at the machine terminals. Thus the amplification factor is 10,000 to 1. If a 10-kw amplidyne is used to control a 1000-kw generator, an overall amplification factor of 1,000,000 to 1 is obtained for an adjustable-voltage control system. This amplification is illustrated by Fig. 61.

The extremely small amount of energy required to excite the shunt field permits the shunt field flux to build up rapidly. As the resistance and reactance of the short-circuited armature is very small, armature flux builds up rapidly and practically in phase with the shunt field flux. The time required by an amplidyne to build up its rated output voltage from zero is but a small fraction of a second, usually between $\frac{1}{20}$ and $\frac{1}{15}$ second. The oscillogram in Fig. 62 shows the voltage build-up for a typical amplidyne from the instant a voltage signal is applied to its field. The time required for reaching rated voltage from zero is between 3 and 4 cycles of a 60-cycle timing wave.

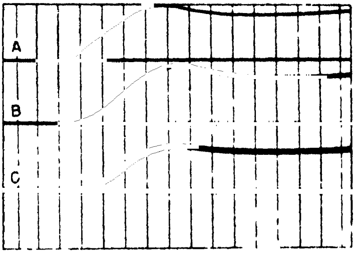


FIG. 62. Oscillogram showing response of amplidyne to control voltage transient. Trace *A*: Control field current. Trace *B*: Short-circuited axis current. Trace *C*: Output voltage. *Note*. Vertical lines designate $\frac{1}{60}$ second time intervals.

The low level of energy required for the excitation of amplidynes permits arranging a multiplicity of fields on the poles, and each field may receive an independent control impulse. Thus an amplidyne may be made to respond to a number of quantities in closed cycle control systems. Speeds of response and accuracies of control and regulation hitherto impossible with conventional exciters may be attained. Because of the importance which the amplidyne has gained for industrial control applications, amplidyne control circuits are discussed in detail in Chapter 13.

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CHAPTER 3

PRINCIPLES OF ALTERNATING-CURRENT MOTOR OPERATION

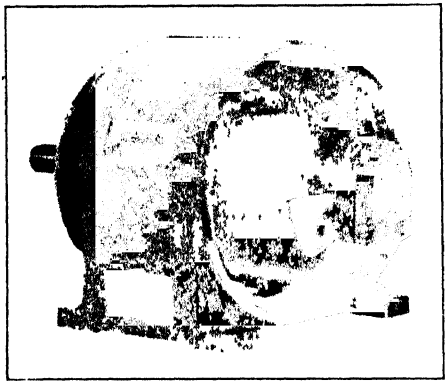
The operation of a-c motors is based on the same dynamo-electric principles that were discussed in connection with d-c motors. To develop torque, there must be interaction of flux and current. To develop speed, there must be an electromotive force interacting with flux.

The most widely used a-c types of motors in industry are polyphase induction motors and synchronous motors. Their characteristics are discussed in detail in this chapter. Because single-phase motors and a-c commutator type motors, although of great importance for appliances and for transportation work, are not frequently used in industrial applications at the present time, they are not treated in this book.

INDUCTION MOTORS

An induction motor consists of a stationary frame or stator which contains the primary winding, the design of which is determined by the number of phases and the number of poles. The rotating member or rotor contains the secondary winding. The rotor winding may consist of bars short-circuited by rings at the end. A motor of that type is called a squirrel cage motor because of the resemblance of the rotor winding to a squirrel cage. A squirrel cage winding is short-circuited in itself, and no external connections may be made to it. Or the rotor winding may be a distributed polyphase winding, the phases of which are terminated at slip rings. Such a motor is called a wound rotor motor, and by means of external connections to the slip rings the electric characteristics of the secondary rotor circuit may be varied, thus affecting the performance of the motor. Shown in Fig. 63*A* is a general-purpose squirrel cage motor. Figure 63*B* is a view of a wound rotor motor.

An induction motor, when its stator is connected to the polyphase line, and the rotor is at standstill, acts as a transformer. Current flows through the primary or stator winding, the magnitude and phase angle of which are determined by the impedance of the motor. That component of current which lags line voltage by 90 degrees determines the flux set up in the stator, and it is called the magnetizing current. It is substantially independent of load on the motor.



A. Squirrel cage motor.

B. Wound rotor motor.

FIG 63. General-purpose a-c induction motors.

In a polyphase motor the flux produced by each phase current reaches its peak in the same sequence as the phases of the applied line voltage. The total flux produced by the various phases acting in combination rotates in space in a direction determined by the phase sequence of the applied line voltage. The speed at which the flux rotates in space is equal to 360 electrical degrees per cycle, or an angle of 360 degrees divided by the number of pairs of poles of the primary winding. It can be expressed in revolutions per minute as follows:

$$\text{Speed of flux rotation in rpm} = \frac{60 \times \text{frequency}}{\text{pairs of poles}} \qquad (35)$$ ●

This rotating flux cuts the conductors of the rotor, and at standstill it generates a secondary voltage, the magnitude of which is determined by the turn ratio between stator and rotor. The generated rotor voltage causes current to circulate in the rotor winding, the magnitude and phase angle of which are determined by the impedance of the rotor circuit. That component of current in phase with the rotor voltage and the flux interacts with the flux and develops a torque which causes the rotor to turn in the same direction that the flux rotates.

Speed in rpm at which the flux rotates in space is the synchronous speed, which is base speed or unity. The difference between synchronous speed and actual speed of the motor is called slip, usually expressed in per unit of synchronous speed.

$$S = 1 - s \qquad (36)$$ ■

where S = motor speed in per unit,
s = slip in per unit.

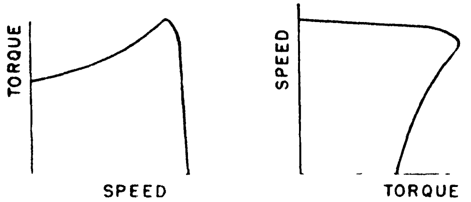
Considering that synchronous speed is proportional to line frequency, slip can be expressed in cycles per second as follows:

$$s(\text{cycles}) = \text{line frequency} \times s \qquad (37)$$ ●

This is the frequency with which the rotor conductors cut the rotating flux; hence it is the frequency of the voltage induced in the rotor conductors. At standstill, slip is unity. When the rotor turns in the direction of flux rotation, which corresponds to normal motor operation, slip is less than unity. If the rotor is driven by an external force against flux rotation, slip is greater than unity. If the rotor is driven by an external force in the direction of flux rotation, but at a speed above synchronous, slip is negative.

When an induction motor is started from standstill and its speed increases, the slip decreases. Likewise frequency and magnitude of the rotor voltage decrease. If it were possible to build a motor without any losses, it would accelerate to synchronous speed. However, the curves resemble each other in their general shape, there is a marked difference between them, especially with regard to starting torque.

Curves 1 apply to a standard normal torque motor. Its rotor consists of a single cage of copper or cast aluminum. Rotor resistance is low, and thus slip and losses are low. The location of the rotor winding close to the air gap results in a low rotor reactance, which accounts for high maximum torque. Starting torque is low; it may be less than unity for large motors.

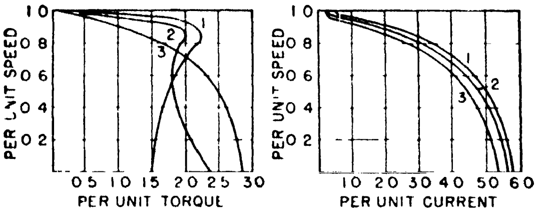


TORQUE - SPEED CURVE, PREFFRRED BY A C MOTOR MANUFACTURFRS

SPEED - TORQUE CURVE, PREFERRED BY CONTROL MANUFACTURERS THIS METHOD IS USED IN THIS BOOK

FIG. 64. Two methods of representing a-c induction motor characteristics.

For applications requiring higher starting torque, a high torque motor can be used which has two squirrel cage windings in the rotor.



SPEED - TORQUE CURVES

SPEED-CURRENT CURVES

FIG. 65. Characteristic curves of different types of squirrel cage induction motors. Curves 1: Normal starting torque motor. Curves 2: High starting torque motor. Curves 3: High slip motor.

One winding, imbedded deeply in the rotor, has low resistance and high reactance. A second winding, located close to the air gap, has high resistance and low reactance. The combined effect of the two rotor windings produces curves 2 in Fig. 65. Slip is slightly higher, maximum torque and starting current somewhat lower than for type 1 motors. Starting torque, however, is considerably increased.

For heavy intermittent-duty drives, requiring frequent acceleration, it is desirable to have available motors with higher maximum torque than the previously described types. Likewise, when a motor drives a high inertia load, its slip should be high, to take advantage of the flywheel effect for reducing torque and line current peaks. The high slip type of motor satisfies these requirements. Its rotor has a squirrel cage winding similar to type 1, but its bars are designed so that the rotor resistance is increased several times. Curves 3 of Fig. 65 apply to this type of motor. Its slip and also running losses are higher than for the other types. Its starting current is a little lower than for types 1 and 2. Starting torque and maximum torque are considerably higher.

Although the curves of Fig. 65 are typical and bring out the salient features of different types of squirrel cage motors, it should be realized that specific values of maximum torque, starting torque, and starting current vary with the speed and frame size of different motors. Actual design data should be procured when controllers are laid out, especially for large motors.

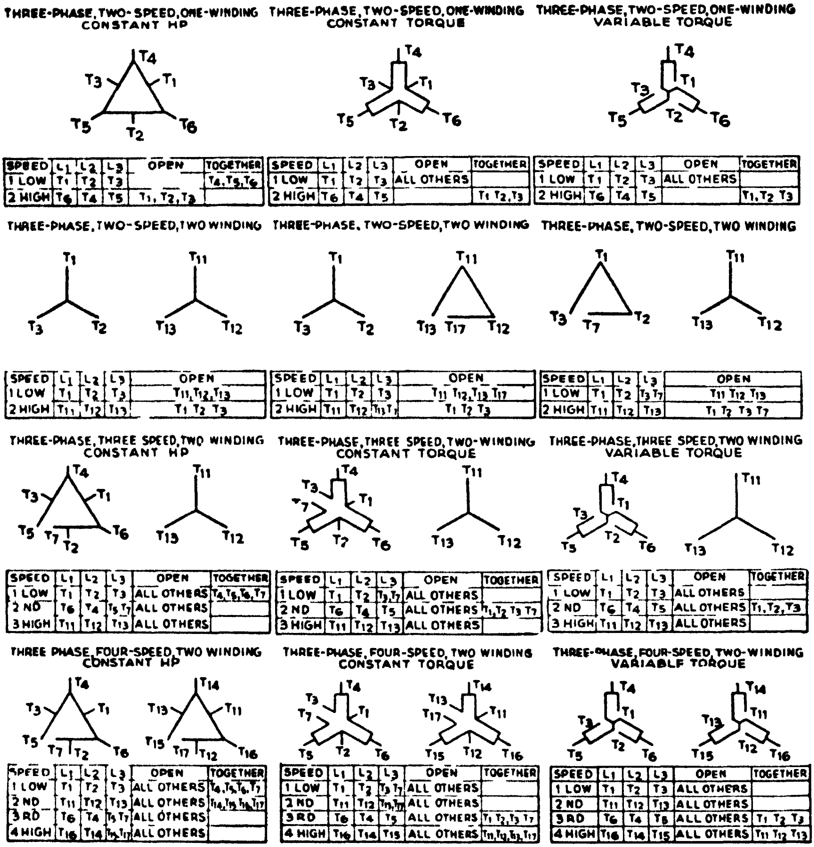
Pole-Changing Motors

Squirrel cage induction motors are basically constant-speed motors, and their speed is determined by line frequency and the number of poles of the stator winding. Specially designed stator windings can be connected for different numbers of poles. Multi-speed motors can operate at several different speeds. Speed control is possible in definite steps, the number and spacing of steps being determined by the design of the stator winding. At each speed step, the motor will operate as a constant-speed motor.

Two types of stator windings are in use for multi-speed motors. Single consequent pole windings can be reconnected to obtain two different numbers of poles. With this type of winding the choice of numbers of poles is restricted to a 2-to-1 ratio. For instance, a consequent pole winding may be wound for 4 and 8 poles, 6 and 12 poles, 8 and 16 poles, etc. If different ratios of speeds are desired, two separate superimposed windings can be arranged in the stator slots, one winding only being connected to the line at any time. The two windings are designed for different numbers of poles, permitting the choice of speed ratios different from 2 to 1.

Either one or both of the superimposed windings may be consequent pole windings; thus motors may operate at three or four different speeds. It is necessary that the speeds obtained with the consequent pole windings have a 2-to-1 ratio. In Fig. 66 the stator connections for commonly used combinations of multi-speed three-phase motors are shown.

According to the torque developed at the various speeds, multi-speed motors are divided into three categories. Constant horsepower motors are able to develop the same horsepower at all speeds. Thus the torque on the various speed points varies inversely with the speed. Constant torque motors develop the same torque on all speed points. Hence the horsepower rating on various speed points varies proportional to speed. Variable torque motors develop a torque on each speed point which is proportional to speed,



THREE-PHASE, TWO-SPEED, ONE-WINDING CONSTANT HP

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	T_3		T_4, T_5, T_6
2 HIGH	T_6	T_4	T_5	T_1, T_2, T_3	

THREE-PHASE, TWO-SPEED, ONE-WINDING CONSTANT TORQUE

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	T_3	ALL OTHERS	
2 HIGH	T_6	T_4	T_5		$T_1\ T_2, T_3$

THREE-PHASE, TWO-SPEED, ONE-WINDING VARIABLE TORQUE

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	T_3	ALL OTHERS	
2 HIGH	T_6	T_4	T_5		$T_1, T_2\ T_3$

THREE-PHASE, TWO-SPEED, TWO WINDING

SPEED	L_1	L_2	L_3	OPEN
1 LOW	T_1	T_2	T_3	T_{11}, T_{12}, T_{13}
2 HIGH	T_{11}	T_{12}	T_{13}	$T_1\ T_2\ T_3$

THREE-PHASE, TWO-SPEED, TWO WINDING

SPEED	L_1	L_2	L_3	OPEN
1 LOW	T_1	T_2	T_3	$T_{11}\ T_{12}, T_{13}\ T_{17}$
2 HIGH	T_{11}	T_{12}	$T_{13}\ T_{17}$	$T_1\ T_2\ T_3$

THREE-PHASE, TWO-SPEED, TWO WINDING

SPEED	L_1	L_2	L_3	OPEN
1 LOW	T_1	T_2	$T_3\ T_7$	$T_{11}\ T_{12}\ T_{13}$
2 HIGH	T_{11}	T_{12}	T_{13}	$T_1\ T_2\ T_3\ T_7$

THREE-PHASE, THREE SPEED, TWO WINDING CONSTANT HP

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	T_3	ALL OTHERS	T_4, T_5, T_6, T_7
2 ND	T_6	T_4	$T_5\ T_7$	ALL OTHERS	
3 HIGH	T_{11}	T_{12}	T_{13}	ALL OTHERS	

THREE-PHASE, THREE SPEED, TWO-WINDING CONSTANT TORQUE

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	T_3, T_7	ALL OTHERS	
2 ND	T_6	T_4	T_5	ALL OTHERS	$T_1, T_2\ T_3\ T_7$
3 HIGH	T_{11}	T_{12}	T_{13}	ALL OTHERS	

THREE-PHASE, THREE SPEED, TWO WINDING VARIABLE TORQUE

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	T_3	ALL OTHERS	
2 ND	T_6	T_4	T_5	ALL OTHERS	T_1, T_2, T_3
3 HIGH	T_{11}	T_{12}	T_{13}	ALL OTHERS	

THREE PHASE, FOUR-SPEED, TWO WINDING CONSTANT HP

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	T_3	ALL OTHERS	T_4, T_5, T_6, T_7
2 ND	T_{11}	T_{12}	T_{13}	ALL OTHERS	$T_{14}, T_{15}\ T_{16}, T_{17}$
3 RD	T_6	T_4	$T_5\ T_7$	ALL OTHERS	
4 HIGH	T_{16}	T_{14}	$T_{15}\ T_{17}$	ALL OTHERS	

THREE-PHASE, FOUR-SPEED, TWO WINDING CONSTANT TORQUE

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	$T_3\ T_7$	ALL OTHERS	
2 ND	T_{11}	T_{12}	T_{13}, T_{17}	ALL OTHERS	
3 RD	T_6	T_4	T_5	ALL OTHERS	$T_1\ T_2, T_3\ T_7$
4 HIGH	T_{16}	T_{14}	T_{15}	ALL OTHERS	$T_{11}, T_{12}, T_{13}, T_{17}$

THREE-PHASE, FOUR-SPEED, TWO-WINDING VARIABLF TORQUE

SPEED	L_1	L_2	L_3	OPEN	TOGETHER
1 LOW	T_1	T_2	T_3	ALL OTHERS	
2 ND	T_{11}	T_{12}	T_{13}	ALL OTHERS	
3 RD	T_6	T_4	T_5	ALL OTHERS	$T_1\ T_2\ T_3$
4 HIGH	T_{16}	T_{14}	T_{15}	ALL OTHERS	$T_{11}\ T_{12}\ T_{13}$

FIG. 66. Commonly used stator connections for multi-speed squirrel cage induction motors.

and the horsepower rating for various speed points is proportional to the square of the speed.

In Fig. 67 speed-torque curves are plotted for typical two-speed motors with a 2-to-1 speed ratio, for constant horsepower, constant torque, and variable torque design. When the motor is switched from the high-speed to the low-speed winding, the low-speed winding develops a considerable amount of retarding torque, which, in constant horsepower motors, may greatly exceed the maximum torque developed by the high-speed winding. This retarding torque is accompanied by high currents. In order to avoid dangerous stresses on the driven machinery, it may be necessary to insert buffer resistance in the low-speed winding during the period of deceleration from high to low speed. The reduction in retarding torque obtained with a given amount of buffer resistance depends on the design data of the specific motor. The motor designer should be asked for his recommendations for a given motor application.

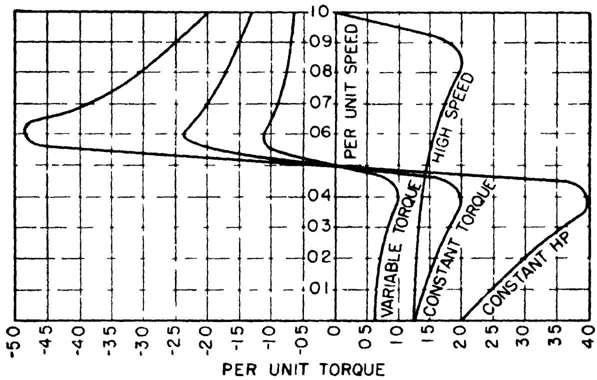


Fig. 67. Typical speed-torque curves of 2-to-1 pole-changing squirrel cage induction motors.

Reduced Voltage Starting

The current drawn from the line during full voltage starting of a squirrel cage induction motor may have undesirable effects on the power system. The resultant drop in the power line voltage may cause light flickers, and when motors above a certain size (depending on the size of the power system) are started it may be necessary to reduce the starting current to an acceptable value by reducing artificially the voltage applied to the motor terminals below full line voltage. Power company rules govern the largest-size motor for which full voltage starting is permissible on a given power system.

A change in voltage applied to the stator terminals results in a change of flux, proportional to primary voltage. Likewise, stator and rotor current vary proportional to applied stator voltage. Since motor torque is proportional to the product of flux and rotor current, torque is proportional to the square of applied stator voltage. The application of reduced voltage to the stator terminals reduces both the starting current and the starting torque.

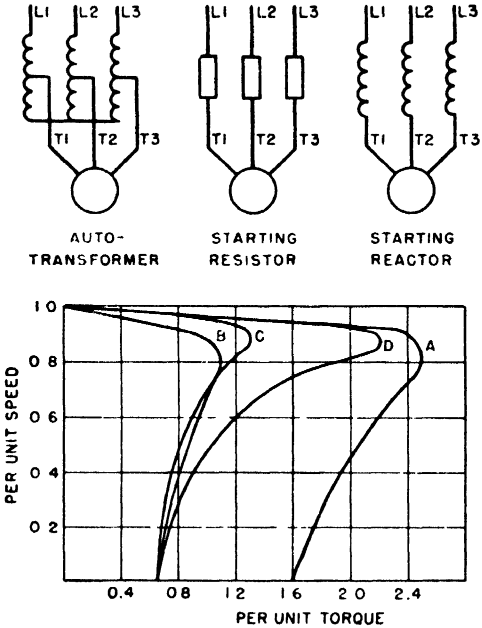


FIG. 68. Methods of reduced voltage starting of squirrel cage induction motors. Curve *A*: Full voltage starting. Curve *B*: Auto-transformer, 0.65 voltage tap. Curve *C*: Starting resistor, 0.65 motor standstill voltage. Curve *D*: Starting reactor, 0.65 motor standstill voltage.

In Fig. 68 three commonly used methods of reduced voltage starting are illustrated, and resultant speed-torque curves are plotted for a typical motor.

Use of an auto-transformer is the most expensive but also the most efficient method of reducing the starting current. During the whole starting cycle, the terminal voltage at the motor is reduced in proportion to the turn ratio of the transformer. Neglecting drop in the transformer, the terminal voltage stays constant. Starting torque and maximum torque are thus reduced proportional to the square of the turn ratio of the auto-transformer. The motor starting current, measured in the motor stator winding, is reduced proportional to the turn ratio of the auto-transformer. Therefore, the starting current, measured in the power line, is reduced proportional to the square of the auto-transformer turn ratio.

Widely used for reducing starting current is the primary starting resistor. The resistance drop reduces the motor terminal voltage. To determine the motor voltage at standstill, it is necessary to know its standstill or locked rotor current and power factor. The drop through the resistor must be subtracted from line voltage vectorially in order to determine the voltage at the motor terminals. The starting torque is proportional to the square of the ratio between motor standstill voltage and line voltage. Starting current is directly proportional to the ratio between motor standstill voltage and line voltage. Expressed in terms of line current, primary starting resistance obtains less reduction in starting current than the auto-transformer, for a given reduction in starting torque. While the motor starts and its speed increases, the stator current decreases, and with it the drop through the starting resistor. Therefore, the motor terminal voltage rises, and maximum torque of the motor is higher than in the auto-transformer starting method.

A starting reactor obtains results similar to a starting resistor. At standstill, the drop through the reactor reduces the motor standstill voltage, the amount of which is determined by subtracting the drop through the reactor vectorially from line voltage. As the starting power factor of most motors is quite low, fewer ohms are required in a starting reactor than in a starting resistor to obtain a given standstill motor voltage. The starting torque is proportional to the square, and the starting current is directly proportional to the ratio between motor terminal voltage and line voltage. As the motor accelerates, its current decreases and its power factor increases. Thus the drop across the reactor swings out of phase with the drop across the motor. The motor terminal voltage rises above the value obtained with a starting resistor, and the maximum torque of the motor is greatly increased thereby.

Another method of reducing the starting current is the use of wye-delta switching of the stator winding. Both ends of the phases of the stator winding are brought out to terminals. First the winding is connected in wye, and then in delta, equivalent to reducing the motor terminal voltage at standstill in the ratio of $1/\sqrt{3}$ to 1.

Wye-delta starting is used widely in Europe but has not become common practice in the United States.

Speed Variation by Frequency Converter

As the speed of an induction motor is determined by the number of poles of the stator winding and the frequency applied to the stator, the speed of an induction motor can be varied by changing the frequency applied to the stator. Synchronous speed of the motor is directly proportional to the applied frequency.

The highest speed at which induction motors can run on a commercial 60-cycle power system is approximately 3600 rpm for two-pole motors. When higher motor speeds are required, for instance for woodworking machine tools and for aircraft model testing, a separate adjustable-frequency power source can be provided for the induction motors. On other applications, such as run-out tables in steel mills, squirrel cage induction motors are advantageous because of their simple mechanical construction. In such cases an adjustable-frequency power supply has been used to feed a group of motors and to adjust the speed of the group by adjusting the frequency.

Magnetizing current and flux of an induction motor is proportional to primary voltage and inversely proportional to frequency. Hence, when an adjustable-frequency control system is laid out, voltage must vary proportional to frequency so that the factor, voltage per cycle, is constant. This factor, volts per cycle, is a characteristic of the induction motor, which is given in the nameplate rating of high-speed squirrel cage motors. The range of frequency over which a given motor may be operated is limited by the mechanical strength of the rotor, the ability to dissipate losses at high speed, and lubrication and life of the bearings. When operated at constant volts per cycle, the motor operates substantially as a constant torque machine, and its maximum torque does not vary greatly over its speed range. However, because of the high standstill reactance at high frequency, the starting torque drops to a very low value as the frequency increases. Motors operated on an adjustable-frequency supply should be started at low frequency and accelerated by raising the frequency.

A simple means of obtaining an adjustable-frequency supply is a frequency converter. In Fig. 69 the principal circuits are indicated. A frequency converter is built like a wound rotor induction motor. Either the stator or the slip rings are connected to a constant frequency source. Either the stator or the rotor winding may be the primary winding. The secondary winding is connected to the load.

The converter is driven by an adjustable-speed motor, such as a shunt wound d-c motor or an adjustable-voltage drive.

At standstill primary frequency is equal to secondary frequency, and the converter acts as a transformer. When the converter is driven in the direction of its rotating flux, the secondary frequency is reduced, and at synchronous speed it becomes zero. If the converter is driven against the direction of flux rotation, the secondary frequency increases. At synchronous speed in this direction, secondary frequency becomes twice primary frequency; at twice synchronous speed, secondary frequency becomes three times primary frequency, and so forth. As long as the primary input voltage stays constant, the volts per cycles on the adjustable-frequency bus stay constant. If it is desired to vary the volts per cycles on the adjustable-frequency bus, for instance on testing equipment used with motors varying widely in size, the input voltage to the converter is varied. This can be accomplished by feeding the primary of the converter from an alternator, or by interposing an adjustable-ratio transformer or booster alternator between a constant voltage line and the converter primary. Volts per cycles on the output side

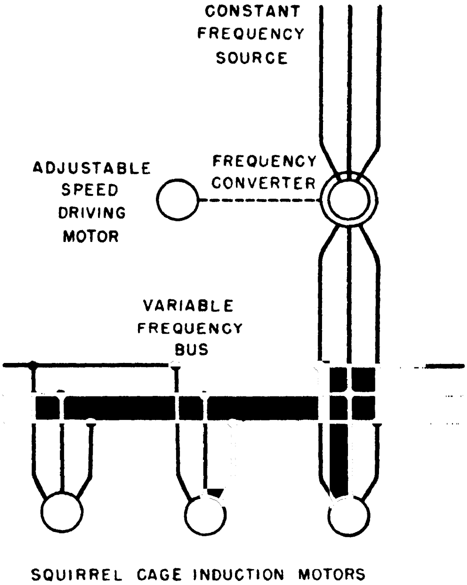

CONSTANT FREQUENCY SOURCE
ADJUSTABLE SPEED DRIVING MOTOR
FREQUENCY CONVERTER
VARIABLE FREQUENCY BUS
SQUIRREL CAGE INDUCTION MOTORS

FIG. 69 Frequency converter system for speed control of squirrel cage induction motors.

of the converter vary directly in proportion to the input voltage applied to the primary.

Control of speed of the induction motors is thus realized by speed control of the frequency converter. Any kind of adjustable-speed motor control can be used, depending upon the type of converter driving motor selected. To avoid burning and pitting of the converter slip rings, it is good practice to arrange the control so that the converter is never permitted to operate at standstill but will always turn at some very low speed.

Reversing

It has been stated before that the direction of mechanical rotation of an induction motor is determined by the direction of rotation

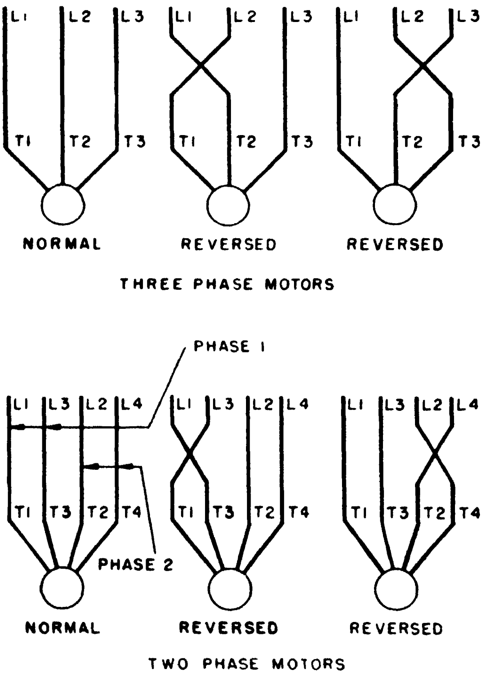


FIG. 70 Methods of reversing polyphase induction motors.

of its flux in space. In a polyphase motor, the direction of flux rotation is determined by the sequence of the phases of the line voltage applied to the motor stator. The sequence of phases can be reversed by interchanging two lines to the motor stator. Hence polyphase induction motors can be reversed by interchanging two of the stator connections.

Figure 70 illustrates methods of reversing for both three-phase and two-phase induction motors.

Regenerative Braking and Plugging

So far, squirrel cage motor operation has been considered under operating conditions where the motor drives a positive load. However, the motor may be driven by the load, and then the motor develops a braking torque, opposing the load torque, in a similar manner as has previously been discussed in connection with d-c motors.

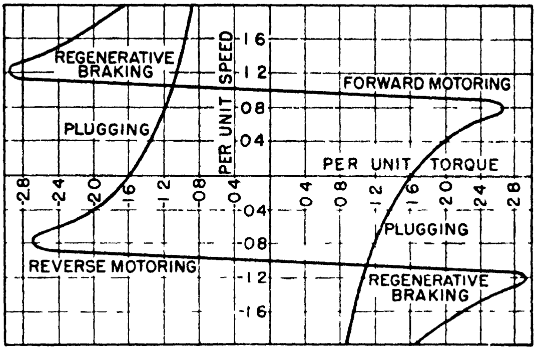


FIG. 71. Typical plugging and regenerative braking performance curves of a squirrel cage induction motor.

If a squirrel cage motor is driven by a load in the same direction as the rotation of its flux, its speed rises above synchronous. The motor acts as an induction generator, taking magnetizing current from the line and feeding power back into the line. Its slip becomes negative, and its speed-torque curve is similar to the motoring curve, except that it is located in the dynamic braking quadrants 2 or 4. Typical speed-torque curves are plotted in Fig. 71. Maximum torque is somewhat higher than for motoring operation, which is due to the influence of stator resistance. The increase in maximum torque may vary from a small percentage for large low-resistance motors to as high as 50 per cent for small high-resistance motors. The motor restrains the load with little rise in speed above synchronous, as long as load torque does not exceed maximum torque of the motor. If maximum torque is exceeded, the motor will become unstable and run away. As the motor draws its excitation from the line, no dynamic braking action is possible when the connection between the motor stator and the a-c power line is interrupted.

A squirrel cage motor may be retarded quickly by plugging. This means that while the motor is running at full speed in one direction, its stator connections are reversed. Thus the motor actually runs in a direction opposite to the rotation of its flux and the slip is greater than unity. Speed-torque curves for plugging are also included in Fig. 71. Plugging torque available at full speed is slightly higher than one half of starting torque, the exact amount depending on the resistance of the rotor winding. The higher the resistance, the higher is the ratio of plugging torque to starting torque. Plugging can be used advantageously to bring a motor, driving an inertia load, to a quick stop, as the plugging torque opposes the overhauling inertia torque of the load. Plugging is not suitable for restraining a load under the influence of gravity, such as a load on a crane hook, because plugging torque decreases with increasing speed.

During plugging operation, motor current is slightly higher than starting current. The energy transmitted from the load to the motor is not fed back into the line but is dissipated within the motor as losses. When applying a squirrel cage motor to a drive which is plugged frequently, care must be taken to select a motor having sufficient thermal capacity to dissipate the losses occurring during plugging operation.

D-C Dynamic Braking [5]

If the stator of an induction motor is excited with direct current, a d-c flux is set up in the motor, which is stationary in space. When the motor is driven by a load, the rotor conductors intersect the d-c flux. An emf is generated in the rotor conductors, causing current to flow in the rotor. This current, in conjunction with the d-c flux, develops torque which is opposed to the torque driving the motor.

Either two phases of the stator are connected to the d-c source, the third phase being idle. This is called the two-lead connection. Or two phases are paralleled and connected to one pole of the d-c source, the third phase being connected to the other pole. This is called the three-lead connection. In Fig. 72 the two methods are indicated, together with a typical set of braking speed-torque curves for various amounts of d-c stator current. The torque that can be obtained with a given amount of d-c excitation varies with the specific design of the motor, its number of poles, and its rotor impedance. For specific applications, braking data must be obtained from the motor designer. However, Fig. 72 is indicative of the shape of the braking curves to be expected.

Braking torque varies with the amount of d-c excitation. Higher average braking torque over the speed range can be obtained than

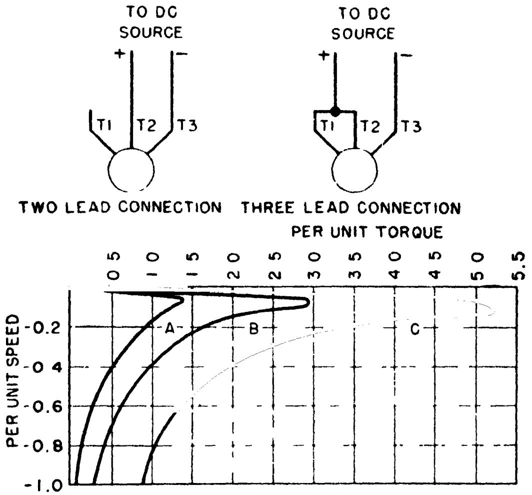


FIG. 72. D-c dynamic braking curves of typical squirrel cage induction motor. Curve *A*: D-c current 1.33 of a-c full load current. Curve *B*: D-c current 2.66 of a-c full load current. Curve *C*: D-c current 4.00 of a-c full load current. All curves drawn for two-lead connection.

with plugging. Thus the d-c dynamic braking connection is suitable for applications where it is desired to decelerate a load rapidly. When the motor has been brought to a stop, the torque becomes zero, and the motor will not start in the opposite direction of rotation, as may happen when deceleration is by plugging.

Effect of Unbalance of Stator Voltage[8, 9]

Any unbalanced polyphase system can be resolved into balanced polyphase systems of positive, negative, and zero sequence by using symmetrical components. The theory of this method of solving polyphase problems is not discussed here in detail. The reader should refer to a standard textbook for a treatment of this theory.

When applying an unsymmetrical polyphase voltage to the stator of an induction motor, zero sequence voltage can be neglected, as it does not develop torque and has no effect on the speed-torque curve. Zero sequence current, which may flow only in a delta-connected stator winding, but not in a wye-connected winding, may increase the motor losses, but that effect can be neglected as it is of no interest to the control engineer.

The effect of positive and negative sequence voltages on the speed-torque curves of an induction motor can be obtained as follows: If the speed-torque curve of the motor is known for rated symmetrical stator voltage and if positive and negative sequence voltages are known in per unit of rated motor voltage, the torque developed by either the positive or the negative sequence voltage component at any speed is equal to normal motor torque multiplied by the square of the ratio of positive or negative sequence voltage to normal voltage. Positive sequence torque can thus be plotted as torque for one direction of rotation, and negative sequence torque can be plotted for opposite direction of rotation. Net torque of the motor is the difference between positive sequence torque and negative sequence torque.

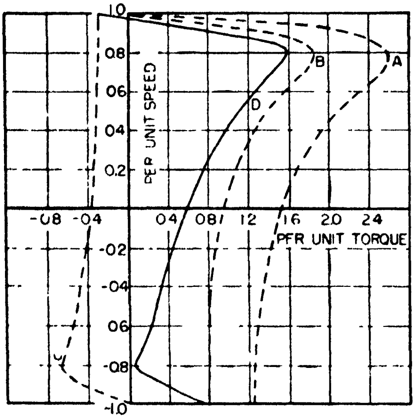


FIG. 73. Effect of unbalanced primary voltage on speed-torque curve of polyphase squirrel cage induction motor. Curve *A*: With symmetrical normal voltage applied. Curve *B*: 0.8 positive sequence voltage applied. Curve *C*: 0.5 negative sequence voltage applied. Curve *D*: Resultant curve for unbalanced voltage applied.

In Fig. 73 speed-torque curves are plotted for a typical squirrel cage motor for a hypothetical unsymmetrical line voltage consisting of 0.8 positive sequence voltage and 0.5 negative sequence voltage. Curve *A* is the basic curve for rated symmetrical voltage applied to the stator. Curve *B* is the characteristic corresponding to 0.8 positive sequence voltage applied to the stator. At any speed point, the torque of curve *B* is 0.64 times the torque of curve *A*. Curve *C* is the characteristic corresponding to 0.5 negative sequence voltage applied to the stator, plotted for phase rotation opposite to curve *B*. For any speed point, the torque of curve *C* is 0.25 times the torque of curve *A*, if curve *A* were plotted for phase rotation opposite to that shown. Curve *D* is the resultant speed-torque curve of the motor, which is the difference between curves *B* and *C*.

A slight unbalancing of the applied stator voltage, such as may occur on commercial systems supplying both motor and lighting loads, has very little effect on motor performance. As long as positive sequence voltage is nearly unity and negative sequence voltage amounts only to a small fraction, the effect on motor performance is negligible. Control systems have been used in which artificial circuits are set up to unbalance the stator voltage, in order to obtain certain performance characteristics. Since both positive and negative sequence voltages introduce losses in the motor windings, whereas the net torque is the difference between positive and negative torque, motor efficiency is reduced. Expressed differently, for a given amount of required motor torque, losses and heating of the motor windings are increased. Control systems based on unbalancing of stator voltage should thus be used with caution.

Single Phasing

A special case of unbalancing the stator voltage of a three-phase or two-phase motor is the loss of one phase of the power supply. It may be caused by the blowing of a fuse somewhere in the system or by burning out or mechanical interruption of one of the conductors of the power supply. Line voltage may still appear across two of the stator leads, and the motor then operates as if it were connected to a single-phase system

If the loss of phase occurs while the motor is running, the motor continues to run with little change in speed. For a given load, current in the stator winding of a three-phase motor rises to approximately 1.73 times the current the motor would draw from a three-phase system. A single-phased two-phase motor draws twice the current it would draw from a symmetrical system. The motor overheats if it is left running single phase continuously. If the loss of phase occurs while the motor is at standstill, it will not start as the starting torque is zero.

A single-phase system can be considered by symmetrical components as being the resultant of two balanced polyphase systems of opposite phase sequence. Each one of the polyphase systems develops torque in the motor, one torque in the positive and one torque in the negative direction of rotation. The net torque of the motor is the difference between positive and negative torque at each speed point. It is possible to determine the single-phase speed-torque characteristic of a given motor over its full speed range if its polyphase characteristics are known. It is necessary to obtain from the motor designer torque, current, and power factor over the range from full positive to full negative speed. These data are given in Fig. 74 for a typical squirrel cage motor.

Torque developed in the forward or positive direction of rotation can be determined by calculating motor impedance for rotation with

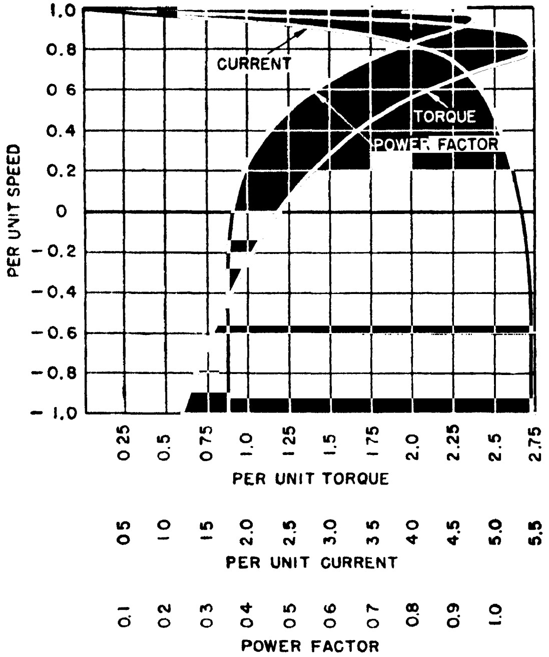


FIG. 74. Torque, current, and power factor curves of typical squirrel cage induction motor.

the flux and against the flux, that is, for positive and negative speed. By using the following symbols, which can be expressed in per unit or in numerical values,

V = line voltage = unity
S = motor speed
I_+ = current for speed S
I = current for corresponding speed $-S$
T_+ = torque for speed S
T = torque for corresponding speed $-S$
Z_+ = motor impedance for speed S
Z = motor impedance for corresponding speed $-S$

motor impedance can be calculated for any speed point from data given in Fig. 74.

$$Z_+ = \frac{V}{I_+\sqrt{3}} \tag{41}$$

$$Z_- = \frac{V}{I_-\sqrt{3}} \tag{42}$$

If Z_+ and Z_- are added vectorially and power factor is used at speed S and $-S$ from Fig. 74, the total impedance becomes

$$Z = Z_+ + Z_- \tag{43}$$

From the torque curve of Fig. 73, T_+ and T_- can be read. Single-phase torque in the forward direction is

$$T_F = T_+ \left(\frac{Z_+}{Z}\right)^2 \tag{44}$$

Similarly, single-phase torque in the reverse direction is

$$T_R = T_- \left(\frac{Z_-}{Z}\right)^2 \tag{45}$$

Total torque of the motor is the difference between T_F and T_R.

In Fig. 75 forward and reverse torque are plotted for the range of speeds from full-speed forward to full-speed reverse. The resultant net torque, the difference between the forward and reverse torque curves, is indicated as the solid curve. At standstill forward and reverse torque are the same, and the resultant starting torque is zero. This is the reason why single-phase motors require auxiliary windings for starting. Once the motor has been started, it can run stable

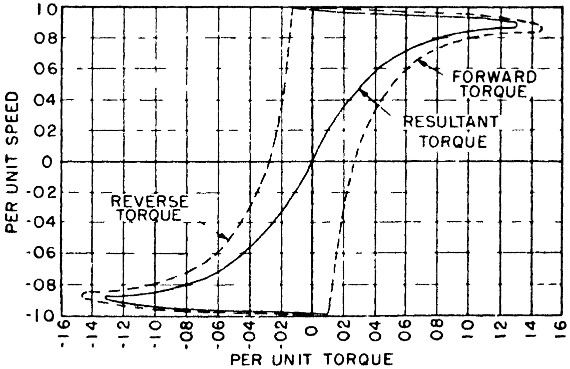


FIG. 75. Single-phase speed-torque curve of squirrel cage induction motor.

in either direction of rotation. Slip is slightly higher and maximum torque somewhat lower than for normal polyphase operation.

WOUND ROTOR MOTORS

With its slip rings short-circuited, the speed-torque curve of a wound rotor motor is very similar to that of a standard normal starting torque squirrel cage motor. As the secondary resistance of wound rotor motors is generally lower than that of squirrel cage motors, starting torque is lower and starting current is higher.

If resistance is inserted in series with the secondary winding, that is to say, with the rotor slip rings, the secondary drop is increased and the slip (or rotor frequency) must increase correspondingly, so that the voltage generated in the rotor balances the drop across the internal and external resistance. To calculate speed-torque curves, it is necessary to determine generated secondary voltage, which is a measure of speed, and secondary current, which is a measure of torque. Expressed in per unit,

$$s = E_2 \qquad (46)\ \blacksquare$$

$$T = I_2 \qquad (47)\ \blacksquare$$

where E_2 = per unit generated secondary voltage,
s = per unit slip,
I_2 = per unit secondary current,
T = per unit torque

A wound rotor motor connected to the line with its secondary winding open-circuited acts as a transformer. Secondary voltage is equal to line voltage multiplied by the transformer ratio between primary and secondary windings. No current flows in the secondary, no torque is developed, and the motor remains at standstill, that is, slip is unity. To express motor operating conditions on a per unit basis, the following base quantities are defined:

Base voltage $E_{2\,\text{normal}}$ = open-circuited standstill voltage between slip rings.
Base current $I_{2\,\text{normal}}$ = secondary full-load current per phase.
Base torque = rated torque.
Base speed = synchronous speed.

Total resistance of the secondary circuit consists of internal rotor resistance per phase and external resistance per phase, which is connected to the slip rings.

$$R_2 = R_i + R_s \qquad (48)$$

where R_2 = total secondary resistance per phase,
R_i = internal rotor resistance per phase,
R_s = external secondary resistance per phase.

To convert resistance in ohms to per unit value, base resistance is defined as follows:

$$\text{Base resistance } R_{2\,\text{normal}} = \frac{E_{2\,\text{normal}}}{\sqrt{3}\,I_{2\,\text{normal}}} \qquad (49)\ \bullet$$

With base R_2 connected in the secondary circuit and base I_2 flowing, the motor develops base torque, secondary voltage equals base E_2, and the slip is unity. In other words, starting torque equals base torque.

Base resistance is generally obtained in ohms from the motor designer, or it can be calculated if open-circuited secondary voltage and full-load secondary current are known. If open-circuited secondary voltage is not given, base resistance can be calculated as follows:

$$R_{2\,\text{normal}} = 249 \times \frac{\text{rated motor hp}}{I_{2\,\text{normal}}^2\,(1 - s)} \qquad (50)\ \bullet$$

Effect of Secondary Resistance on Motor Speed

During normal operation the torque delivered by the motor is well below maximum torque, and the speed is above the speed at which maximum torque occurs. Within this range, the speed-torque curves are straight lines and the relation between speed and torque can be expressed in per unit as follows:

$$\begin{aligned} s &= 1 - S \\ &= T(R_i + R_s) \end{aligned} \qquad (51)\ \blacksquare$$

For any given amount of torque, slip increases and speed decreases with increasing secondary resistance. If speed is plotted versus torque, the intersection between the speed line and the base torque line is a direct measure of secondary resistance, as shown in Fig. 76.

Starting torque T_s is the torque developed by the motor at standstill or unity slip. When the secondary resistance is high, say 0.5 or more, the reactance of the motor is only a small fraction of the resistance, and it can be neglected. The speed-torque curve is a straight line between full speed and zero speed. Starting torque is then inversely proportional to secondary resistance. In per unit,

$$T_s = \frac{1}{R_i + R_s} \qquad (52)\ \blacksquare$$

In order to lay out a secondary resistance type speed controller for a specific motor, it is necessary to know its internal resistance R_i.

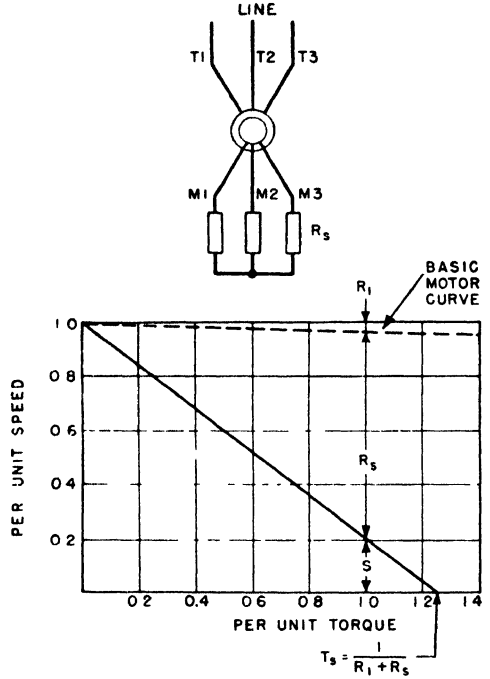


FIG. 76. Effect of secondary resistance on speed of wound rotor induction motor.

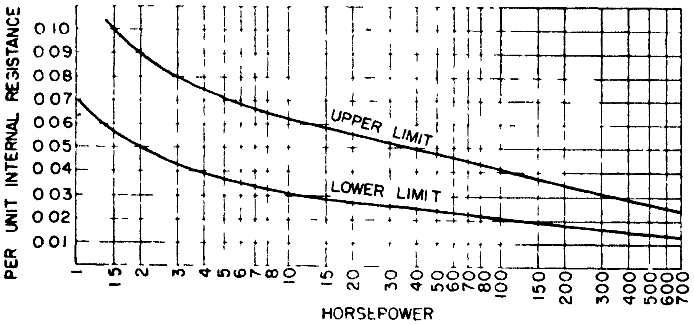


FIG. 77. Internal resistance of continuously rated wound rotor induction motors.

Expressed in per unit, internal resistance is equal to the normal slip of the motor at full load. (See formula 51 for $T = 1$ and $R_s = 0$.) In Fig. 77 internal resistance of standard continuously rated motors in per unit is plotted versus motor size. Indicated is a band between upper and lower limits. Slip increases with the number of poles. It also varies somewhat with motors of different designs. The lower limit is an average for 4-pole motors, and the upper limit is an average for 10- to 16-pole motors. For intermittent rated motors, internal resistance is somewhat higher.

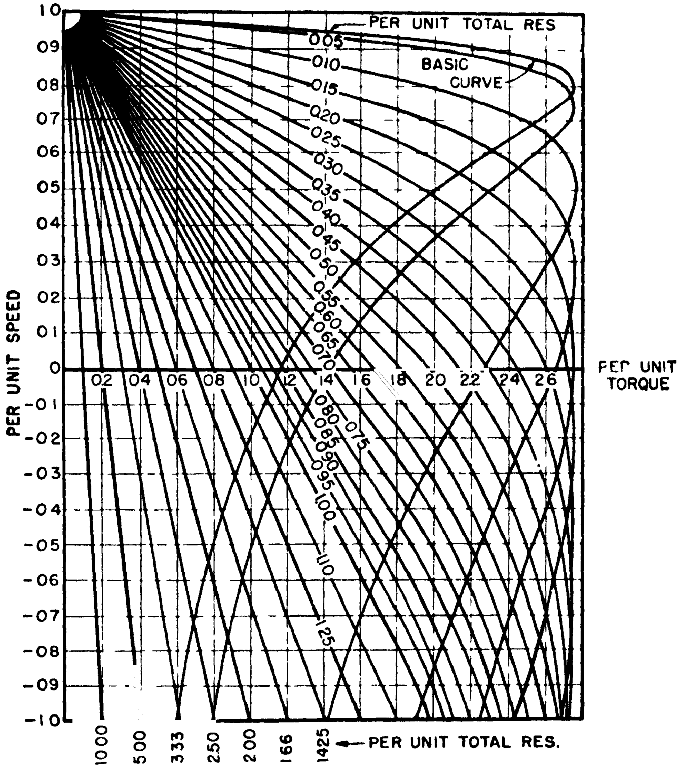


Fig. 78. Speed-torque curves of a typical wound rotor induction motor with varying secondary resistance.

External secondary resistance has no effect on maximum torque but it affects the slip at which maximum torque occurs. In Fig. 78 speed-torque curves for a typical wound rotor motor are plotted for various amounts of total secondary resistance, both for the motoring and the plugging quadrant. The curves resemble those of a d-c shunt motor with variable resistance in series with the armature. The amount of external resistance has little effect on speed at light loads. It is impracticable to use wound rotor motors as adjustable-speed motors for reductions in speed to less than one half at full load because the slope of the speed-torque curves at greater speed reductions becomes too steep, and slight variations in torque cause undesirably high speed changes.

If a greater amount of speed reduction at full load is desired, the motor may be built with a pole-changing stator winding, the same that is used frequently for squirrel cage motors. Thus it is practicable to reduce the speed to one half of each no-load speed by inserting secondary resistance. For instance, a motor with a 1-to-2 speed range by pole changing can be used as an adjustable-speed motor down to one quarter of its high speed. When motor characteristics are reduced to per unit values, pole changing influences only the characteristics of the stator winding but not of the rotor winding of a given motor. Pole changing does not affect the per unit secondary data, and a given amount of per unit secondary resistance will obtain the same per unit speed reduction with the high- and low-speed stator connections.

Dynamic Braking and Plugging[6]

Dynamic braking and plugging performance can be obtained with wound rotor motors in the same manner as was described for squirrel cage motors. In addition, performance both during dynamic braking and plugging operation can be influenced by changing motor secondary resistance. Figure 79 shows dynamic braking and plugging curves for a typical wound rotor motor for various amounts of secondary resistance and for both directions of rotation.

When a wound rotor motor is driven by a load in the same direction of rotation as its flux, the motor runs at a speed above synchronous and acts as an induction generator, feeding power into the line. With no resistance connected to the slip rings, that is, with the slip rings short-circuited, the speed rises slightly above synchronous, as long as the maximum torque is not exceeded. As the internal resistance of wound rotor motors is generally lower than that of squirrel cage motors, maximum dynamic braking torque is only slightly higher than maximum motoring torque. If resistance is inserted in the rotor circuit, the dynamic braking speed rises above synchronous. At unity torque the rise in speed above synchronous is equal in per unit to the total secondary resistance in per unit. As during motoring performance, dynamic braking speed varies in direct proportion to overhauling torque on the motor shaft. Dynamic braking at speeds above synchronous can be used for lowering a load under the influence of gravity as long as secondary resistance is kept sufficiently low to prevent excessive motor speeds.

A wound rotor motor may be plugged by reversing two stator leads. The motor then turns in a direction opposite to rotation of flux. The load is restrained by the counter torque the motor develops. With the slip rings short-circuited, the plugging curve is similar to the

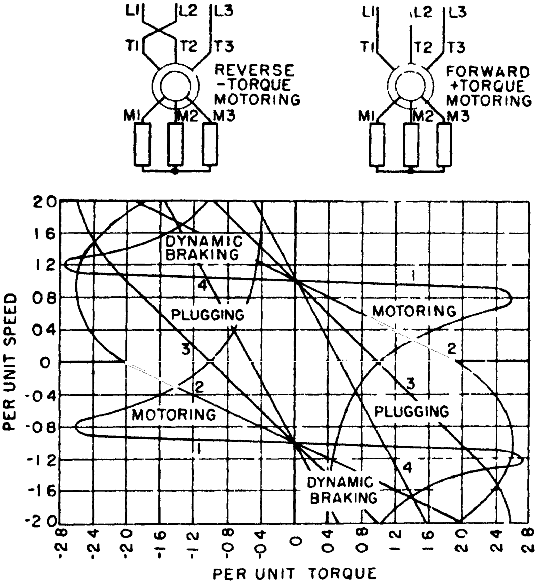


FIG. 79. Typical plugging and dynamic braking performance curves of a wound rotor induction motor. Curve 1: Basic motor curve. Curve 2: Secondary resistance 0.5. Curve 3: Secondary resistance 1.0. Curve 4: Secondary resistance 2.0.

plugging curve of a squirrel cage motor. It is impracticable to plug a wound rotor motor with no resistance in the secondary circuit, because the resultant high rotor current would damage the slip rings and brushes.

Inserting resistance in the rotor circuit materially alters the plugging curves. With secondary resistance of unity or more, the speed-torque curves become straight lines in the plugging quadrant. The plugging torque rises with rising speed. At negative synchronous speed the plugging torque is twice the starting torque. The corresponding plugging current is twice the starting current. Thus, by proper selection of secondary resistance, it is possible to adjust plugging torque and plugging current to suit the requirements of the drive. Plugging can be used for retarding a load and bringing the motor to a quick stop. It is also possible to lower a load that is under the influence of gravity by counter torque, and stable operation results, as long as sufficient secondary resistance is used so that the plugging torque increases with speed.

Unbalanced Secondary Resistance

So far performance of wound rotor motors with external secondary resistance has been considered under the assumption that the same amount of resistance is inserted in each phase of the rotor; in other words, that the rotor circuit is balanced. Using unequal amounts of resistance in the rotor phases has advantages under some operating conditions. Figure 80 illustrates commonly used unbalanced rotor connections.

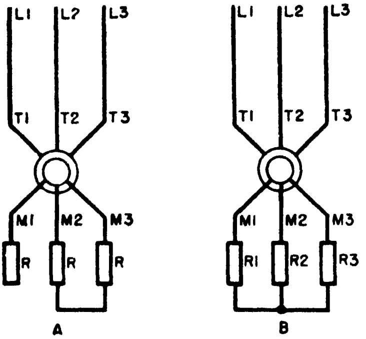


FIG. 80. Effect of unbalanced resistance in rotor phases A: Leaving one rotor phase open: $R_{\text{eff}} = 2R$. B: Unequal resistance in each rotor phase: $R_{\text{eff}} = \dfrac{R_1R_2 + R_2R_3 + R_3R_1}{R_1 + R_2 + R_3}$.

If resistance is connected only in two rotor phases and the third phase is left open, the effective resistance is twice the actual resistance per phase. This connection is used quite frequently on the first point of manual starters, as it simplifies starter design and cuts in half the amount of resistance required to obtain a given starting torque. Closing the third rotor phase on the second point of the starter balances the rotor circuit and doubles the starting torque obtained on the first point. As the unbalance in the rotor circuit causes torque pulsations and additional mechanical stresses in the motor, starting with one rotor phase open should be used only for motors of 75-hp rating or less.

When manual drum switches are used to change the amount of resistance in the secondary circuit, the design of the switch development is greatly simplified by changing resistance in unbalanced steps. For calculating motor performance with unequal amounts of resistance in the rotor phases, the equivalent effective resistance R_{eff} can be calculated by the following approximate relation. Let $R1$, $R2$, $R3$ be the total resistance in each of the three rotor phases. Then

$$R_{\text{eff}} = \frac{R1R2 + R2R3 + R3R1}{R1 + R2 + R3} \tag{53}$$

On account of torque pulsations caused by the unbalance in the rotor phase current, motors larger than 75 hp should not be operated continuously with unbalanced rotor connections.

D-C Dynamic Braking [5]

If the stator of a wound rotor motor is excited with direct current and the rotor driven by a load, dynamic braking torque is developed which opposes the load torque. The speed-torque characteristics are influenced by the magnitude of the d-c exciting current, just as in squirrel cage motors. Furthermore, the speed attained at a given overhauling torque can be varied by changing the amount of resistance in the rotor circuit governing the drop in the secondary circuit, which in turn must be counterbalanced by the emf generated in the rotor. With d-c flux at a constant value, speed increases with increasing secondary resistance.

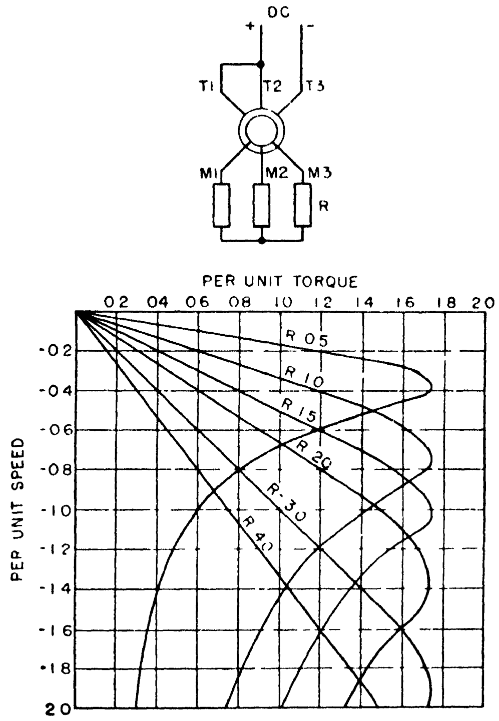


FIG. 81. Typical d-c dynamic braking performance curves of wound rotor induction motor with d-c excitation of 1 3 full load a-c current.

To plot speed-torque curves, it is necessary to obtain from the motor designer the amount of resistance necessary to obtain synchronous speed at base torque, the maximum torque, and the amount of d-c excitation. If d-c excitation is held constant, speed at a given torque varies directly in proportion to secondary resistance. For instance, halving the resistance halves the speed.

For estimating purposes, the following relation can be assumed for average wound rotor motors. If a d-c excitation equal to 1.3 times full load a-c rms current is applied to the stator phases, maximum torque is 1.75. Synchronous speed at base torque is obtained with a secondary resistance of 3.0. In Fig. 81 speed-torque curves for this average case are plotted for various amounts of secondary resistance.

With a given amount of secondary resistance, torque increases with increasing speed, as long as maximum torque is not exceeded. D-c dynamic braking is well suited to restrain a load that is under the influence of gravity, and it has been used for lowering control of a-c motor-driven crane hoists.

Unbalancing of Stator Voltage

The voltage applied to the stator may be unbalanced artificially, and the degree of unbalance can be varied, for instance, by the use of an auto-transformer with overhanging winding across two stator phases. Such a connection is shown in Fig. 82. Inserting resistance in the rotor circuit obtains speed-torque characteristics quite different from those of a wound rotor motor with balanced stator voltage.

Speed-torque curves are plotted in Fig. 82 for a hypothetical motor having a maximum torque of 2.75. Secondary resistance is assumed to be 0.6. The dotted curves represent the speed-torque curves obtained for positive sequence voltages V_+ and negative sequence voltages V_- equal to 0.85 and 0.6 line voltage. As torque varies as the square of applied voltage, maximum torque is reduced to 2.0 and 1.0, respectively.

If positive and negative sequence voltages are applied to the motor simultaneously by unbalancing the stator voltage, the net torque developed by the motor is equal to the difference of the torques developed by the positive and negative sequence voltages individually. An extreme case of unbalance is obtained when motor stator terminals T_2 and T_3 are connected together to some point on the auto-transformer. This is equivalent to applying single phase to the stator, and positive and negative sequence voltages are equal. Curve A is plotted under the assumption that V_+ and V_- are both 0.85 line voltage V.

The resultant curves show that zero torque is developed at standstill. The motor does not start, but it retards an overhauling load.

Curve *B* is plotted under the assumption that T_2 and T_3 are connected to the auto-transformer in such a manner that V_+ is 0.85 and

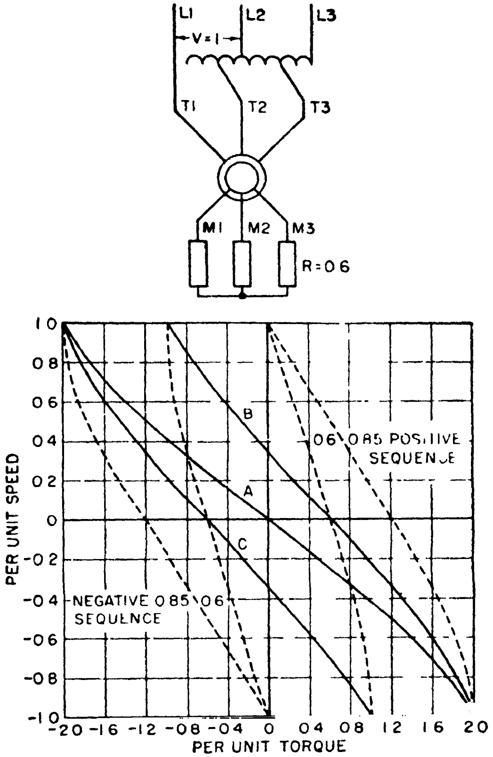


FIG. 82. Effect of unbalance of stator voltage on performance of wound rotor induction motor. Curve *A*: Positive and negative sequence voltages, each 0.85. Curve *B*: Positive sequence voltage 0.85, negative sequence voltage 0.60. Curve *C*: Positive sequence voltage 0.69, negative sequence voltage 0.85.

V_- is 0.6 line voltage. Curve *B* is the difference between dotted curve for 0.85 positive sequence and 0.6 negative sequence. Likewise, curve *C* is plotted under the assumption that T_2 and T_3 are reversed on the auto-transformer so that V_+ is 0.6 and V_- is 0.85 line voltage. Curve *C* is the difference between the dotted curves for 0.85 negative sequence and 0.6 positive sequence.

Curves *B* and *C* show that no-load speeds below synchronous can be obtained. Curves *A*, *B*, and *C* are well suited to retard an overhauling load and to restrain a load that is under the influence of gravity. Unbalancing of the stator phases is used in connection with the lowering operation of hoists. The speed-torque characteristics are desirable, but unbalancing of the motor has the disadvantage that the stator current is unbalanced and losses are equal to the sum of the losses caused by the positive and negative sequence voltages, whereas the developed torque is equal to the difference of the torques developed by the individual voltage sequences.

Power Selsyn Operation [10]

If two wound rotor induction motors are so interconnected that corresponding phases of the stator windings are connected to the same

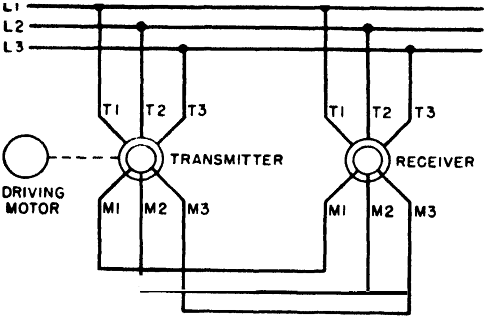


FIG. 83. Power selsyn system consisting of two wound rotor induction motors.

phases of the line and corresponding rotor phases are interconnected, the rotor voltages of both motors must be of equal magnitude, and both motors must operate at the same per unit speed. As long as the two rotor voltages have the same phase angle, the two rotors will retain the same angular position in space, that is, the two motors will run in synchronism. If one of the two rotors lags in angular position with respect to the other, a phase shift occurs between the two rotor voltages, which, in turn, causes a circulating current to flow between the two rotors. This current develops a torque in the direction to reduce the angle of lag between the two rotors, and this torque keeps the two rotors in step as long as the maximum torque which the combination is able to develop is not exceeded. The torque is called synchronizing torque. A system of induction motors as described is called a power selsyn (from *self-syn*chronizing) system.

In Fig. 83 the connections of a simple power selsyn system are shown schematically. It consists of two wound rotor motors. They may or may not have an equal number of poles. Their rotor open-circuit voltages must be the same so that the rotor voltages match at any speed. If one of the induction motors, the transmitter, is driven by a motor, it transmits torque to the second induction motor, the receiver, which rotates at the same relative speed (as determined by its number of poles) as the transmitter. Power selsyns can be used to operate two mechanically separated devices at the same speed and in synchronism with each other by means of electrical interconnections only.

Power selsyns may be driven either in the same direction or in the opposite direction as the rotation of flux. The maximum torque that can be developed by the combination varies with relative speed. In Fig. 84 the torques of both transmitter and receiver are plotted versus speed for mechanical rotation with or against flux rotation. Base torque is the rated torque which the selsyn machines would develop, when operated as induction motors. When selsyns are operated in the same direction as the field, the synchronizing torque decreases rapidly as synchronous speed is approached. For this reason, selsyns should not be operated at speeds above two thirds synchronous speed, unless they operate against flux rotation.

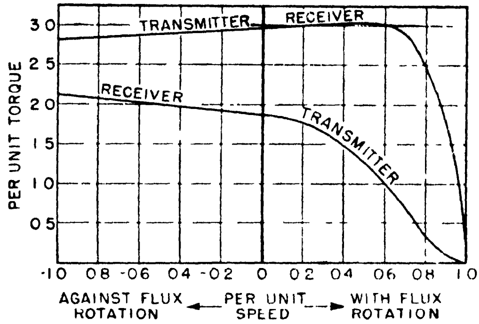


FIG. 84. Maximum torque characteristic of two identical wound rotor motors operating as power selsyns.

If the selsyn system is subjected to rapid changes in speed or in torque, the system may tend to hunt. Whether or not the system will actually hunt depends largely on design constants of the selsyn machines and mechanical constants of the drive. If a drive is found to hunt, this hunting can be remedied by inserting resistance in the stator phases of the receiver. The maximum torque of the receiver is thereby reduced, but the receiver follows speed changes of the transmitter with less tendency to overshoot and hunt.

Power selsyns may be used to hold two independent motors in step. Referring to Fig. 83, both the transmitter and the receiver may be connected to driving motors. The selsyn system then does not transmit all the required driving torque to the receiver but only sufficient torque to keep the two motors in synchronism.

The synchronizing torque holding the selsyn motors in step varies with the angle of displacement between the rotors. The angle of displacement is measured in electrical degrees; 360 electrical degrees are one revolution divided by the number of pairs of poles. Synchronizing torque is zero at zero degrees displacement and at approximately 180 degrees displacement. The torque reaches a maximum at approximately 90 and 270 degrees displacement.

Before a power selsyn system can be started, it is necessary to synchronize or "lock in step" the selsyn motors at standstill. If three-phase voltage were applied and the selsyn motors were standing still with a large angular displacement between their rotors, a high torque would be developed, pulling the motors in step. However, the motors would in most cases overshoot the "locked in step" rotor position and start to run as induction motors, failing to synchronize. If single-phase voltage is first applied, a synchronizing torque is developed which locks the rotors in step. The motors, however, cannot start with single-phase excitation, as the starting torque is zero. A very satisfactory method to start power selsyns is the three-step method illustrated in Fig. 85. On the first step, single-phase voltage is applied to the stators of both selsyn motors, the third stator phase of each motor being left disconnected. The synchronizing torque reaches a maximum near 180 degrees displacement, and the selsyn motors are pulled together in a direction toward the zero displacement position. On the second step, the third stator phases of the two selsyns are connected together. The torque curve approximates a sine wave, with maxima at 90 and 270 degrees displacement. The maximum torque, however, barely equals rated motor torque. On the third step, the third stator phases are connected to the line so that three-phase excitation is applied to the two selsyn motors, and the maximum torque rises considerably above the single-phase value. This rise pulls the rotors together to less than 30 degrees displacement, the exact angle depending on the load torque the selsyns have to overcome. The two selsyn motors are then firmly locked in step, and the selsyn system is ready to be accelerated.

Although a number of experimental circuits have been worked out to synchronize power selsyn motors while they are running, none of them is sufficiently simple and reliable to be used in practice. Controllers for power selsyns must be designed so that the selsyn motors are synchronized at standstill, before the system starts to rotate.

Whereas the foregoing explanation of power selsyn operation is based on a system involving two selsyn motors, it is possible to make up a selsyn system consisting of three or more selsyn motors. Either a multiplicity of individual motorized drives may be kept in synchronism by power selsyns or one transmitter may transmit power to a multiplicity of receiver units. In such a system, resistance should be connected in the stator phases of the receiver units to forestall any tendency of the system to hunt because of unequal torque peaks to which the various receiver units may be subjected.

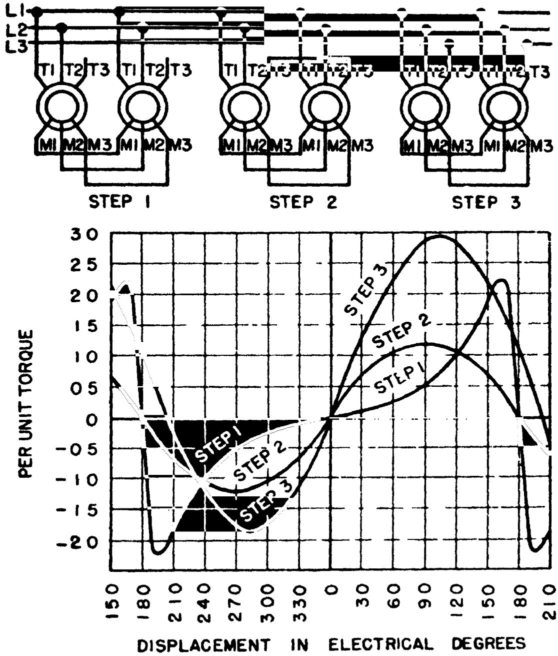


Fig. 85. Typical torque-angle curves for three-step starting sequence of power selsyn system.

Speed-Regulating Sets [11]

The speed of an induction motor for a given torque is determined by its secondary voltage, which is proportional to its slip. In the squirrel cage motor and the wound rotor motor with short-circuited rings, the secondary voltage is determined by the internal resistance drop in the rotor. If resistance is connected in series with the slip rings of a wound rotor motor, the secondary voltage is equal to the internal drop across the rotor resistance plus the drop across the external resistance. The frequency of the secondary voltage is equal to the frequency of the primary power supply multiplied by the slip, called the slip frequency. Neglecting stator losses, the mechanical output of the motor is equal to the electrical input, multiplied by the speed in per unit, and the loss in the internal and external rotor resistance is equal to the electrical input multiplied by the slip in per unit. As the drop across the secondary resistance varies with rotor current, that is, with torque or load, it is not possible to obtain constant speed with varying load by inserting resistance in the rotor circuit.

Introducing into the rotor circuit, from an external source, a voltage of proper magnitude, phase angle, and frequency makes it possible to vary the motor speed. Additional rotating machinery is required to produce the external secondary voltage. Such combinations of machines are called speed-regulating sets. The amount of speed variation with respect to synchronous speed which can be obtained is called the range, which is equal to the maximum slip that can be produced. Speeds below synchronism are obtained by introducing a voltage which adds to the voltage drop in the rotor circuit. Speeds above synchronism are obtained by impressing on the rotor a voltage in the opposite sense from the rotor voltage drop. Speed-regulating sets for speed control below synchronous are called single-range sets, and those permitting speed control both below and above synchronous are called double-range sets.

By varying not only the magnitude but also the phase angle of the voltage impressed on the rotor, the phase angle of the secondary current can be shifted so that a portion of the magnetizing current of the motor is supplied from the rotor circuit instead of the stator. This shift results in an improvement of the power factor of the motor, as viewed from the supply line.

The size of the machines of a speed-regulating set is determined by the slip energy they must handle. This energy is equal to the rating of the induction motor, multiplied by the maximum slip or range for which the set is designed. Because of the cost of the machines, speed-regulating sets are economical only for large motors and for a limited range. If a speed range above two to one is required or if motors of small or medium size are involved, the use of conversion apparatus and adjustable-voltage d-c drives may prove more economical.

In the following paragraphs a number of speed-regulating systems are described which have found practical use.

Kraemer Sets

Kraemer sets use d-c machines to transform the slip energy and to supply the voltage impressed on the rotor of the main induction motor. Shown in Fig. 86 are the basic circuits of two types of sets.

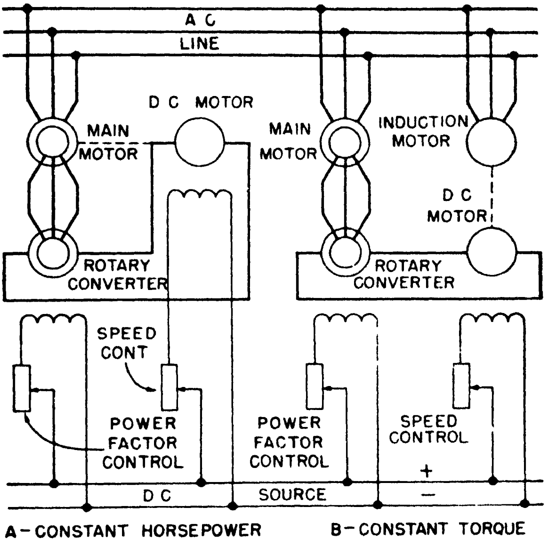


FIG. 86. Principal connections of Kraemer speed-regulating sets.

The slip rings of the main motor are connected to the slip rings of a rotary converter, the commutator of which is connected to the commutator of a d-c motor. In Fig. 86A the d-c motor is coupled to the main motor shaft. Thus the slip energy flows from the main motor rotor, through the rotary converter, into the d-c motor, and is utilized as shaft output of the main motor. This set is capable of producing constant horsepower over its speed range. In Fig. 86B the d-c motor is coupled to an induction motor, which is driven as an induction generator and feeds the slip energy back into the power line. This set is able to operate over its speed range at constant torque. A constant voltage d-c supply must be available to furnish excitation for the synchronous converter and the d-c motor.

The speed of the main motor is varied by changing the excitation of the d-c motor, which controls the voltage across the commutator of the rotary converter. This in turn determines the voltage across the rotary converter slip rings, which is impressed on the main motor slip rings. The speed range that can be obtained with Kraemer sets is solely a question of cost, as with sufficiently large d-c machines it would be possible to reduce the main motor speed to zero. Power factor correction can be obtained by overexciting the rotary converter. Design limitations of the rotary converter make it impractical to improve the power factor beyond approximately 0.95.

To start a Kraemer set, the main motor is first started and brought to normal speed with a conventional resistance type starter. In a constant torque set, the d-c induction motor set is also started. With no excitation on the d-c motor, the slip rings of the main motor are switched from the starting resistor to the rotary converter. Excitation is then applied to the d-c motor, and the main motor assumes a speed corresponding to the voltage produced by the d-c motor.

On account of the small amount of slip energy available near synchronous speed, the rotary converter becomes unstable at low slip frequency. This limits Kraemer set operation to speeds obtaining slip frequencies above 2 cycles, and Kraemer sets are used only as single-range sets. By reversing the excitation of the d-c motor it is possible to accelerate an unloaded Kraemer set through synchronous speed, and stable operation above synchronous speed can be obtained without difficulty. However, the "dead zone" of 2 cycles below and above synchronous speed, within which the main motor cannot deliver any appreciable amount of torque, make double-range operation of Kraemer sets impracticable.

Scherbius Sets

In a Scherbius set the slip rings of the main motor are connected to the commutator of a so-called Scherbius machine. This machine is built similar to a conventional d-c machine. Three sets of brushes are arranged on the commutator so that three-phase power can be taken off. The field structure is excited at slip frequency through an auto-transformer. Thus the frequency of the voltage appearing at the commutator brushes equals slip frequency. By tap-changing of the auto-transformer, the magnitude of the voltage across the commutator of the Scherbius machine, and correspondingly the slip of the main motor, can be varied. By suitable design of the Scherbius machine, the phase angle of its commutator voltage can be deflected so that the power factor of the main motor is improved to approximately 0.95.

Figure 87A shows the basic connections of a constant torque Scherbius set. The Scherbius machine is coupled to an induction machine. The slip energy is transmitted from the main motor rotor, through the Scherbius machine, to the induction machine, which feeds the energy back into the line. Therefore, this set operates at constant torque over its speed range. The Scherbius machine could be coupled directly to the shaft of the main motor. The slip energy would then be transmitted back to the main motor shaft as mechanical energy, and the set would operate over its speed range at constant horsepower.

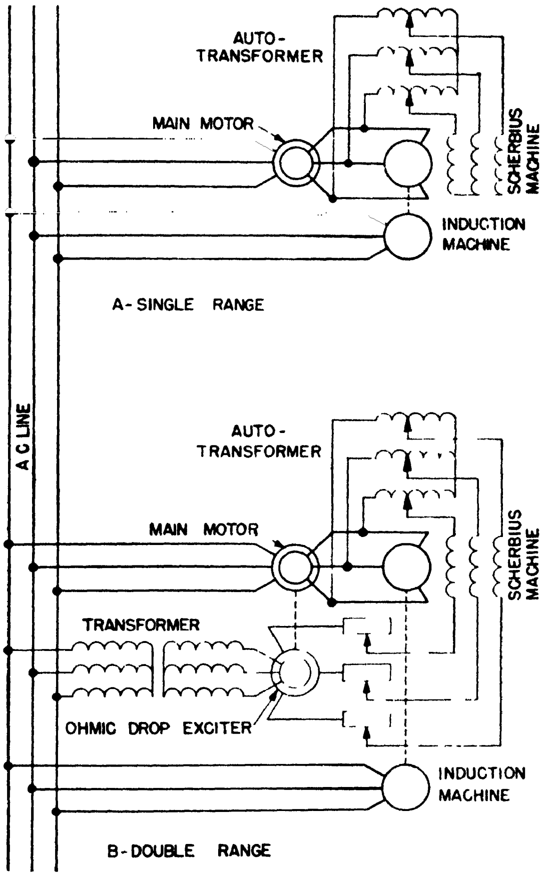


FIG. 87. Principal connections of scherbius speed-regulating sets.

On account of commutation limitations of Scherbius machines, the speed range is limited to a slip frequency of 18 cycles. Thus the relative speed range of the main motor is greater on a 25-cycle system than on a 60-cycle system. When synchronous speed is approached, slip frequency and slip energy decrease. At synchronism, slip frequency and voltage across the Scherbius machine are zero, and no voltage is available to overcome the drop across the resistance of the main motor rotor. The set shown in Fig. 87*A* cannot operate at, or be accelerated through, synchronous speed. The set can operate only below synchronous speed. It is a single-range set.

To operate a Scherbius set as a double-range set through synchronous speed, an additional machine is used, called the ohmic drop exciter. Its basic circuits are indicated in Fig. 87*B*. The ohmic drop exciter is coupled to the main motor. It consists of an armature with slip rings at one end and a commutator at the other end. There is no stator. The slip rings are excited at line frequency through a transformer. The ohmic drop exciter acts as a frequency changer, and a voltage at slip frequency appears across the commutator. This voltage is fed to the field winding of the Scherbius machine. A resistor in series with the ohmic drop exciter is adjusted so that the exciter voltage equals the drop across the resistor and the Scherbius machine field winding.

At synchronous speed of the main motor, the ohmic drop exciter produces a d-c voltage sufficient to excite the Scherbius machine, which in turn generates sufficient voltage to overcome the resistance drop in the main motor rotor. Stable operation at synchronous speed is possible. A Scherbius set with ohmic drop exciter can be accelerated through synchronism and it operates as a double-range set.

As compared with a Kraemer set, the size of the regulating machines is reduced for a given total speed range, as the range of the Scherbius set can be divided into half range above and half range below synchronous speed. In other words, for a given total range the Scherbius set operates only at one half slip, either plus or minus.

Frequency Changer Sets

Basic circuits of speed-regulating sets with frequency changers are indicated in Fig. 88. Diagram *A* pertains to a constant torque set. The slip rings of the main motor are connected to the commutator of a frequency changer, the slip rings of which are connected to the line through a tap-changing transformer. The frequency changer is built like an ohmic drop exciter, except that it has a larger rating. Coupled to the main motor is a small synchronous generator which produces a frequency corresponding to actual motor speed. To this generator is connected a small synchronous motor which drives the frequency changer and supplies its losses. Thus the frequency changer rotates at a speed corresponding to actual motor speed, and the frequency of the voltage across the frequency changer slip rings is equal to line frequency.

Slip energy flows from the main motor slip rings through the frequency changer and back into the line. Hence this set operates at constant torque over its speed range. By changing taps on the transformer, the voltage across the frequency changer slip rings is varied. This voltage, in turn, varies the voltage across the frequency changer commutator and the speed of the main motor. Power factor correction can be obtained to some extent by shifting the commutator brushes of the frequency changer.

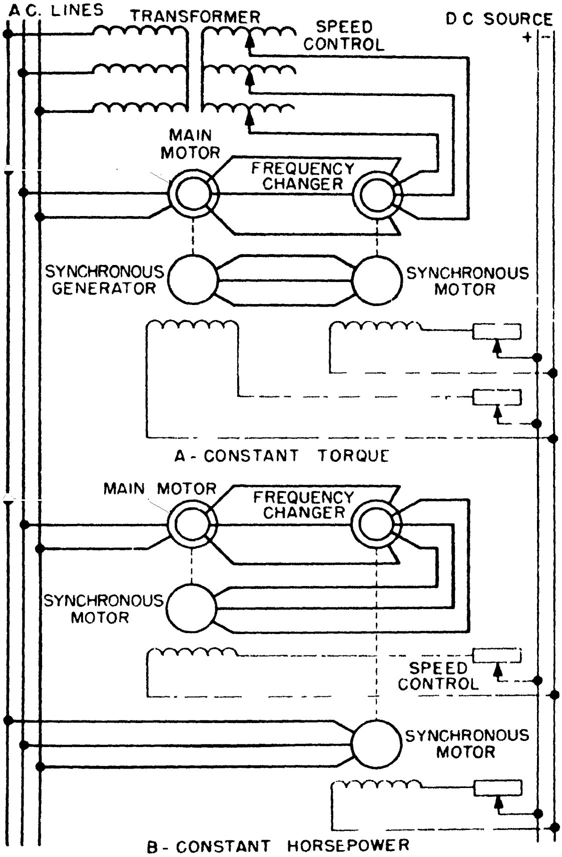


FIG. 88. Principal connections of frequency changer speed-regulating sets.

At synchronous speed of the main motor, the frequency changer is driven at synchronous speed, and direct current appears across its commutator, overcoming the resistance drop in the main motor rotor. Stable operation at synchronous speed is possible, and frequency changer sets can be built for double-range operation. The speed range that can be obtained is determined by the commutating limit of the frequency changer.

Frequency changer sets can also be built for constant horsepower operation, as indicated in Fig. 88*B*. The slip rings of the frequency changer are connected to a synchronous motor coupled to the shaft of the main motor. The driving motor of the frequency changer is connected to the line, and the frequency changer runs at synchronous speed. The slip energy is fed from the frequency changer slip rings to the synchronous motor and utilized as mechanical energy through the main motor shaft. The voltage across the frequency changer and, correspondingly, the speed of the main motor are varied by adjusting the field excitation of the synchronous motor coupled to the main motor shaft.

Doubly Fed Induction Motor [12]

Speed adjustment of a wound rotor motor can be obtained by connecting the stator to a line of fixed frequency and the slip rings to a synchronous generator of adjustable frequency. Such an arrangement is shown in Fig. 89. The main motor slip rings are connected to a synchronous generator, which is driven by an adjustable-speed d-c motor. This motor can either be a conventional d-c motor, provided a suitable d-c supply is available, or the motor may be connected to an

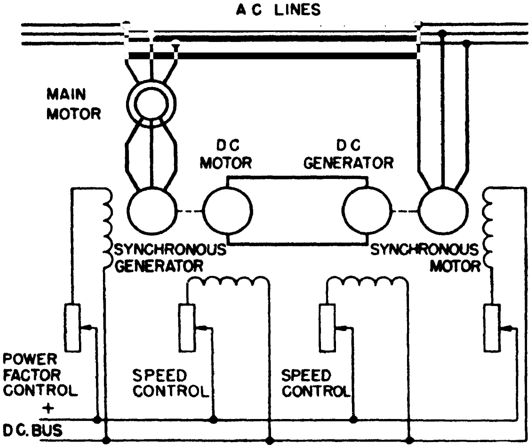


FIG. 89. Doubly fed wound rotor induction motor with speed-adjusting set.

adjustable-voltage d-c generator, which in turn is driven by a synchronous or induction motor. Varying the speed of the d-c motor by adjusting the d-c generator voltage varies the frequency of the synchronous generator and thus the main motor speed. The power factor of the main motor can be varied by adjusting the excitation of the synchronous generator. The slip energy flows from the main motor, through the synchronous generator, and through the adjustable-voltage set back to the line. Therefore, this system is essentially a constant torque system.

As compared with other regulating systems, more rotating machinery is employed. However, several operating advantages offset this disadvantage. As no commutator type machines are used in the main motor secondary circuit, the speed range is not limited. It is possible to reduce the main motor speed to standstill, permitting starting of very large motors, up to 40,000 hp or more with a minimum of line disturbance. With the main motor stator disconnected from the line, the adjustable-voltage d-c drive is started, and the frequency of the synchronous generator is brought up to line frequency. With the main motor at standstill, line frequency appears across the stator terminals, and the main motor stator can be synchronized with the line. After the stator is connected to the line, the main motor can be accelerated by reducing the speed of the synchronous generator.

As the speed of the main motor is determined by the speed of the d-c adjustable-voltage set, it is easy to arrange for fine and accurate automatic speed control. All the refinements that can be built into adjustable-voltage control systems, such as closed cycle control, can be applied to this type of induction motor speed control. It is possible also to regulate the main motor power factor by automatic control of the field excitation of the synchronous generator.

SYNCHRONOUS MOTORS[20]

It has been stated before that an induction motor can operate at synchronous speed only if a voltage is impressed on its rotor. As slip at synchronous speed is zero, frequency of the voltage impressed on the rotor is zero; in other words, direct current flows through the rotor. If direct current is maintained at sufficient strength, a flux is set up stationary with respect to the rotor. The poles of he rotor flux are attracted by opposite poles of the rotating flux set up by the stator winding. Thus the rotor rotates at the same speed with which the stator flux rotates in space, defined previously as the synchronous speed. It is determined by the number of poles (which must be equal for the stator and rotor) of the motor and the line frequency applied to the stator. In Table 3 synchronous speeds are listed for various numbers of poles and line frequencies.

TABLE 3

Synchronous Speeds for Various Numbers of Poles and Line Frequencies

Number of Poles		*Speed at*	
	25 Cycles	*50 Cycles*	*60 Cycles*
2	1500	3000	3600
4	750	1500	1800
6	500	1000	1200
8	375	750	900
10	300	600	720
12	250	500	600
14	214	428	514
16	188	375	450
18	166	333	400
20	150	300	360
22	136	273	327
24	125	250	300
26	115	231	277
28	107	214	257
30	100	200	240
32	94	188	225
36	83	167	200
40	75	150	180

For reasons of economy in design, the field structure of synchronous motors consists usually of a rotor with salient poles. As a matter of principle, either the stator or the rotor may be the d-c excited field member. In practically all cases, however, the rotor is the field member and the stator is connected to the line, with the advantage that the stator winding can be insulated easily for high voltages. Also, large currents do not have to be carried through slip rings. As compared with induction motors, synchronous motors have the following advantages. Efficiency is higher. By proper control of the d-c field excitation, the power factor of the motor can be made unity, or even leading, so that synchronous motors improve the power factor of an industrial system. From a mechanical point of view, a synchronous motor has simpler rotor construction than an induction motor, and its air gap is larger. Some source of direct current must be available, either from an existing d-c shop system or from an exciter that is either directly coupled to or belt driven from the synchronous motor shaft.

Figure 90 is a view of a slow-speed synchronous motor, rated 500 hp, 300 rpm, 2300 volts, 60 cycles. The connections to the d-c field coils are brought out to slip rings. Stator terminals are at the bottom. The motor is intended for driving a compressor, on the shaft of which the rotor will be assembled by the compressor builder.

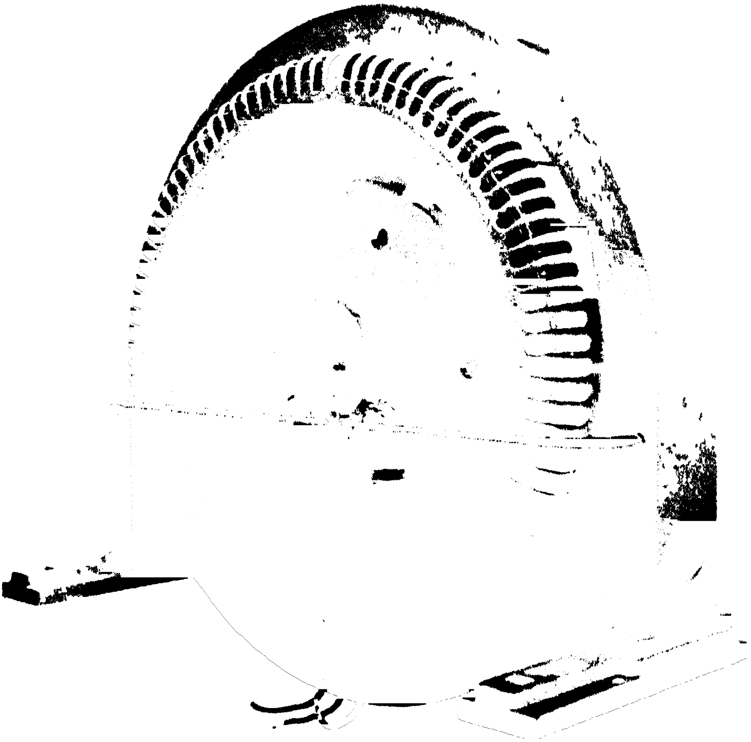


FIG. 90. Slow-speed synchronous motor without shaft

The direction of rotation of a synchronous motor depends upon the direction of rotation of the stator flux. Synchronous motors can be reversed in the same way as induction motors, namely, by reversing two of the stator leads.

Synchronous motors are strictly constant-speed motors, and the only possible way to vary their speed is to vary the frequency of the voltage applied to the stator. Such a system of speed control is impracticable. Because of the rigid speed characteristic that does not permit any speed change with load, synchronous motors are unsuited for parallel operation on the same mechanical load.

When the speed of a synchronous motor is called constant it must be understood that this pertains only to average speed. The instantaneous speed does change with variations in load. As the rotation of a synchronous motor depends upon the attraction of unequal stator and rotor poles, it is possible that the angular relation between the axis of the stator poles with respect to the axis of the rotor poles undergoes changes with changes in torque, resulting in instantaneous speed changes. There is a maximum torque that the motor can deliver, called the pull-out torque. If it is exceeded, the motor pulls out of step and stalls. As torque is proportional to flux and armature (or stator) current, pull-out torque is a direct function of the product of field current and line voltage.

A synchronous motor containing only a stator and a d-c excited rotor winding develops torque at synchronous speed but at no other speed. It cannot develop any starting torque. When synchronous motors were introduced, they were started at no load by auxiliary motors, and then synchronized to the line. To obtain starting torque, enabling the motor to accelerate to a sufficiently high speed to permit synchronizing the motor to the line, a squirrel cage winding is now provided on the rotor. This winding consists of bars imbedded in the pole faces and short-circuited by end rings. This winding is also called damper or amortisseur winding because it has the additional effect of damping torque and instantaneous speed oscillations upon sudden variations in load.

From the point of view of operation, the following phenomena are of interest to the control engineer:

1. Control of acceleration and deceleration, which has primarily to do with the operation of the motor as an induction motor, with the d-c field not excited.
2. Application of d-c field excitation, after the motor has been accelerated to a speed slightly below synchronous speed, to effect automatic synchronizing.
3. Control of the d-c field excitation, after synchronization has taken place, to obtain specific operating performance.

Starting as a Squirrel Cage Motor[13]

The starting characteristics of synchronous motors with a squirrel cage winding are essentially the same as those of squirrel cage induction motors. Starting torque and starting current depend largely upon the resistance of the squirrel cage winding, which can be influenced by the selection of cross section and material of the bars and a considerable latitude is left to the motor designer. A low-resistance squirrel cage winding produces a low starting torque and a low slip at full load, which is of advantage for synchronizing the motor. Also a low-resistance squirrel cage winding is more effective as a damper winding in suppressing torque oscillations. A high-resistance squirrel cage obtains high starting torque, necessary for many applications. On the other hand, the slip at full load is increased, and the effectiveness of the damper winding is impaired. Generally speaking, high-speed motors of a given rating have a higher starting torque than low-speed motors. Shown in Fig. 91 are typical starting torque and current curves for high-speed and low-speed synchronous motors.

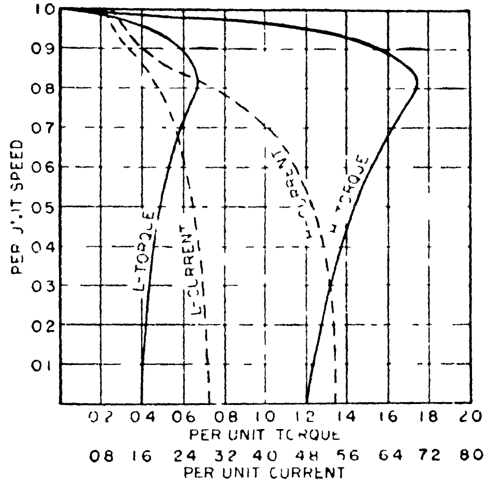


FIG. 91. Starting torque and current of typical high-speed and low-speed synchronous motors. Curves *H*: High-speed motor. Curves *L*: Low-speed motor.

If the power system permits, synchronous motors can be started by applying full voltage to the stator terminals in the same manner as described for squirrel cage motors. If system requirements demand a reduction in starting current, reduced voltage starting is used, and either auto-transformers, starting resistors, or starting reactors may be employed to reduce the stator terminal voltage. Motor torque varies as the square of the ratio of applied terminal voltage to normal voltage.

After the motor has attained synchronous speed, the squirrel cage winding does not carry current, except when it acts as a damper winding, in case the axis of the rotor flux shifts with respect to the axis of stator flux under the impact of sudden load changes. Therefore, squirrel cage windings are not designed to carry starting current continuously. Precautions must be taken to prevent overheating of the squirrel cage winding, should the motor fail to synchronize and attempt to run as an induction motor for a prolonged period of time.

While the motor is accelerating, the field winding on the rotor intersects the stator flux. As the field winding consists of a large number of turns, high voltages of the order of 10,000 volts or more might be induced in the field winding, if it were left open-circuited. During the starting period, the field winding should be connected to a discharge resistor so that current may flow in it. This current has a demagnetizing effect and prevents a build-up of voltage beyond a safe value. The proper amount of discharge resistance to be used depends on the design of the field structure and should be obtained from the motor designer. Short-circuiting of the field winding results in a reduction of the available starting torque, and, when particularly heavy starting requirements are to be met, it may be necessary to leave the field winding open circuited. If this is the case, the field winding must be sectionalized, to keep the voltage induced in each section at a safe value.

For extra heavy starting duty, synchronous motors have been built with a distributed damper winding, similar to the rotor winding of a wound rotor induction motor. This winding is connected to slip rings, and the motor can be started like a wound rotor motor with external resistance connected to the damper winding slip rings.[11]

Part-Winding Starting

High-speed synchronous motors have high starting current as compared with starting torque. On motors of several hundred horsepower rating and larger, the starting current can be reduced by arranging the stator winding in several parallel circuits, which are connected to the line in several consecutive steps. Thus external equipment necessary for reduced voltage starting is eliminated. The stator connections for a two-step part-winding starting motor are indicated in Fig. 92. The stator winding is arranged in two parallel branches per phase. On the first step, one half of the winding is connected to the line. On the second step, the remaining half of the winding is connected to the line.

Torque and current values, as a function of speed, which are obtained with such motors vary considerably, depending on the design characteristics of the specific motor. In Fig. 93 starting torque and starting current curves are given for a 400-hp, 720-rpm motor. With only part of the stator winding energized, a substantial reduction of starting current and a corresponding reduction of the starting torque are obtained as compared with the full stator winding being energized.

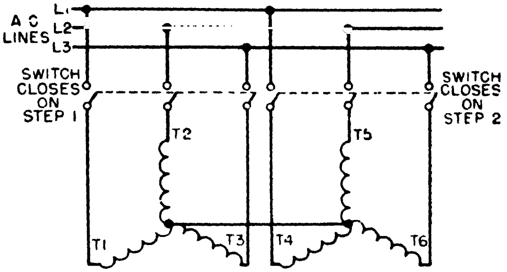


FIG. 92. Typical stator connections of a two-step part-winding starting synchronous motor

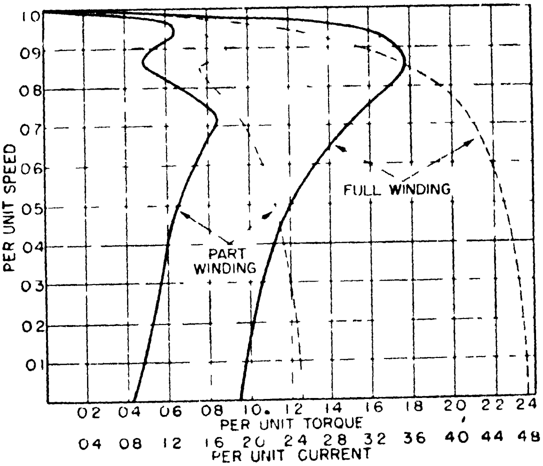


FIG. 93. Starting characteristics of a 720-rpm two-step part-winding starting synchronous motor. Solid curves: Torque. Broken curves: Current.

The stator winding may be subdivided into more than two circuits. Motors with three-circuit stator windings, permitting starting in three steps, have been built.

Plugging and Dynamic Braking[15]

On some applications, such as rubber mills, it is necessary to bring the motor to a rapid stop within a few revolutions. One method is to remove field excitation and to reverse the stator phases. The motor is plugged, and its squirrel cage winding produces plugging torque. This method of decelerating is simple, but the amount of plugging torque available is limited and cannot be varied by external means. Also steps must be taken to prevent reversing of the motor by disconnecting the motor from the line when it has come to a stop.

Another way to obtain rapid deceleration is by dynamic braking. The motor is disconnected from the line, and the stator winding is connected to an external resistor, field excitation remaining established. The motor then acts as a synchronous alternator, driven by the load, and the kinetic energy of the motor and the driven machinery is dissipated in the dynamic braking resistance. No reversing takes place when the motor has come to a standstill.

The dynamic braking torque varies with the amount of dynamic braking resistance. A maximum amount of average braking torque, that is, a minimum number of revolutions between full speed and standstill, is obtained with a dynamic braking resistance of

$$R_{DB} = \frac{X_{DT}}{\sqrt{3}} \text{ ohms} \qquad (54)$$ ●

X_{DT} is the transient reactance of the motor in the direct axis. This value is not apparent from the usually published motor data and must be obtained from the motor designer.

Synchronizing[16, 17, 19]

After a synchronous motor has been started and accelerated to the maximum speed (or minimum slip) it is able to attain as an induction motor, field excitation is applied by connecting the field winding to a d-c source. A synchronizing torque is then developed which must overcome the load torque, the torque corresponding to the losses of the motor out of synchronism, and accelerate both motor and load from minimum slip to synchronous speed. Depending upon the condition of the load and the design of the motor, there is a certain amount of slip which must not be exceeded or the motor will fail to synchronize.

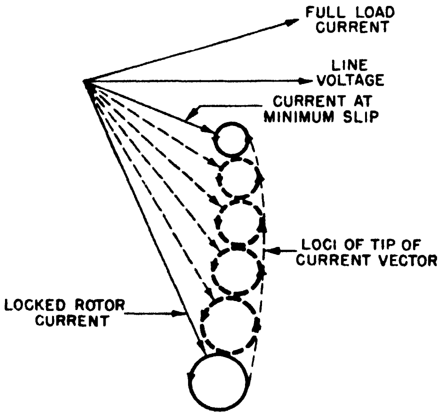
If the load torque is small, for instance, in a motor generator set where the only load consists in friction and windage of the generator, it is not too important at which point in the starting cycle field excitation is applied. If only sufficient time is allowed for the motor to come up to full induction motor speed, field may be applied without any particular precautions, and the motor will pull in step. However, if the motor has to synchronize against an appreciable amount of load torque, certain precautions have to be taken to apply field at the most advantageous point of the starting cycle.

To understand the performance of the motor near synchronous speed, it is necessary to consider the effect of the saliency of the rotor. As the rotor is not a smooth cylinder but carries salient poles, the reluctance of the rotor path to the stator flux varies. When the axis of the stator flux lines up with the rotor poles, the reluctance is low. When the axis of the stator flux falls in between the rotor poles, the reluctance is high. Variations in reluctance cause the reactance of the motor to vary, depending on the relative position of the rotor with respect to the stator flux. As the rotor slips with respect to the rotating stator flux, current, power factor, and torque vary periodically, and the instantaneous values deviate from the average value.

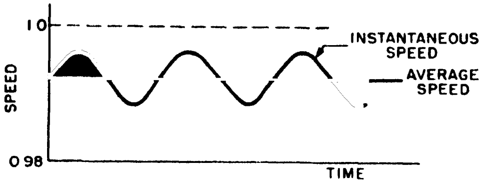
In Fig. 94 the effect of rotor saliency is indicated. Upper sketch A is a vector diagram of line voltage and current during starting. The locked rotor current, that is, the starting current at the instant voltage is applied to the stator, is large and lags the line volage by nearly 90 degrees. The circle at the end of the current vector is the locus of the current vector tip, representing the periodic variations both in magnitude and in power factor of current due to the influence of varying reactance. As the motor accelerates, the magnitude of the current decreases and the power factor increases, as is indicated by the dotted current vectors, until minimum slip is reached. The upper solid current vector represents this condition. For comparison, the full-load current is also indicated, corresponding to operation at synchronous speed. It leads line voltage by an angle which depends on the magnitude of field excitation.

In lower sketch *B* is indicated the actual speed which the motor attains at the end of its starting cycle as an induction motor. Because of saliency of current and torque, instantaneous speed varies periodically above and below average speed. If field is applied while the motor accelerates from a point of minimum speed to a point of maximum speed within a speed cycle, a lesser amount of synchronizing torque is required to accelerate the motor to synchronous speed. Conversely, while the motor is decelerating from a point of maximum speed to a point of minimum speed, a greater amount of synchronizing torque is required for acceleration. This leads to the conclusion that the exact instant at which field is applied is of importance in determining whether or not a given motor will synchronize under load.

While the motor is operating out of synchronism, the rotor slips with respect to the stator flux. The relative position of the rotor poles with respect to the poles of the stator flux changes periodically. The angle, in electrical degrees, between the rotor axis and the stator flux axis at which excitation is applied to the motor has an important bearing on the amount of load torque against which the motor is able to pull into sychronism.



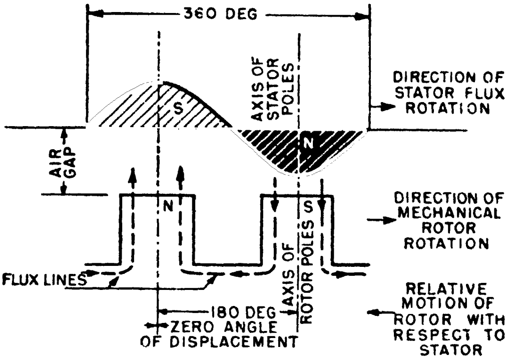
A - VECTOR DIAGRAM OF CURRENT DURING STARTING



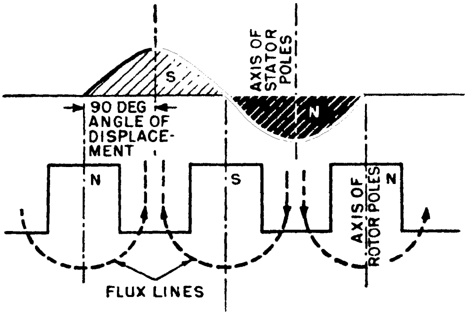
B - DEVIATION OF INSTANTANEOUS SPEED FROM AVERAGE SPEED

Fig. 91. Effect of saliency on starting performance of synchronous motor.

Shown in Fig. 95 is the effect of the relative position of the rotor poles with respect to the stator poles. Two poles of the stator and rotor are shown, developed in a straight line. The direction of stator flux rotation and mechanical rotor rotation is to the right. The slip of the rotor, that is, the relative movement of the rotor with respect to the stator flux is to the left. Upper sketch *A* shows the instant at which the axis of the stator poles coincides with the axis of the rotor poles. Flux linkages between stator and rotor are maximum. Correspondingly, magnetic reluctance is low and reactance is high. Stator current is minimum, and voltage induced in the rotor field winding is zero. This position corresponds to the position the rotor assumes when the motor operates in synchronism with the field excited, except that the rotor lags the stator by a small angle determined by the load. Synchronous operation depends on high flux linkages between stator and rotor.


360 DEG
AXIS OF STATOR POLES
S
N
DIRECTION OF STATOR FLUX ROTATION
AIR GAP
N
S
DIRECTION OF MECHANICAL ROTOR ROTATION
AXIS OF ROTOR POLES
FLUX LINES
RELATIVE MOTION OF ROTOR WITH RESPECT TO STATOR
180 DEG
ZERO ANGLE OF DISPLACEMENT

A-STATOR AND ROTOR POLES LINED UP



B-STATOR AND ROTOR POLES DISPLACED 90 DEG.

FIG. 95. Effect of displacement of synchronous motor rotor with respect to stator flux.

In lower sketch *B* the instant is shown at which the rotor has slipped back 90 degrees. Flux linkages between stator and rotor are minimum because the reluctance offered to the flux is maximum. Stator current is maximum, and current induced in the rotor field winding is maximum in the positive direction, that is, in a direction to maintain the flux.

A criterion for the most favorable angle of rotor position at which field should be applied is based on the following considerations. If field is applied in a rotor position which obtains a condition of flux linkages between stator and rotor similar to the one obtained during synchronous operation, available torque for synchronizing motor and load is highest. The most favorable angle is obtained when the rotor lags the stator flux by a small angle. In that position flux linkages are high and voltage induced in the rotor field winding is just rising from zero in a positive direction. The most unfavorable angle is somewhat beyond the 90-degree displacement position. Flux linkages are low, and induced rotor voltage is just decreasing from maximum, changing in a negative direction.

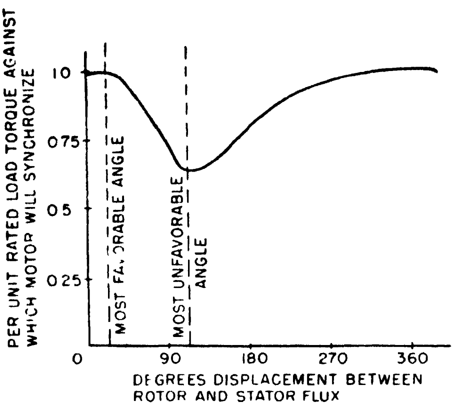


FIG. 96. Effect of angle at which field is applied on pull-in torque of synchronous motor.

This condition is indicated in Fig. 96. Load torque, expressed in per unit of full-load torque, against which a given motor will synchronize is plotted versus the angle of rotor displacement, at which field excitation is applied. There is definitely a favorable and an unfavorable range. The exact location of the most favorable and unfavorable angle changes as much as 60 degrees with different motors, and so does the amount of available pull-in torque. However, the general shape of the curve is typical.

Operation under Overload [18]

Each synchronous motor has a rated full-load torque, a pull-in torque at which it synchronizes, and a pull-out torque at which it loses synchronism or falls out of step. At rated full-load torque, the rotor poles lag the stator poles by an angle, called the load angle. If the torque increases, the load angle increases. At a load angle of approximately 90 degrees or somewhat higher, the torque of the motors reaches a maximum, called the pull-out torque. If the load torque increases beyond that amount, the load angle is further increased, but the motor torque decreases. As a result, the rotor slips relative to the stator flux, the motor loses synchronism, and stalls. If the field remains connected to the d-c source, torque pulsations occur,

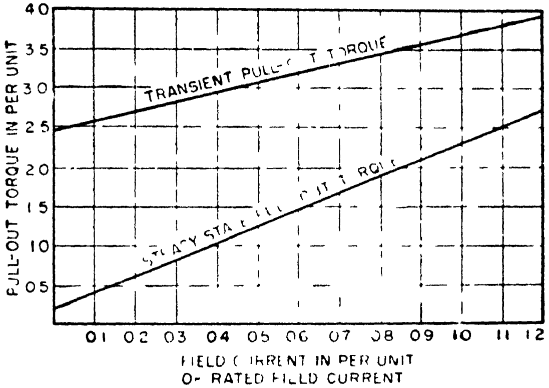


FIG. 97 Pull-out torque of a typical synchronous motor.

which at standstill may exceed three times rated torque. The stator current rises considerably, and the power factor becomes lagging. To prevent damage to the motor and driven machinery, field excitation should be removed as quickly as possible when a synchronous motor falls out of step.

Whether or not the motor should also be disconnected from the line depends on the character of the load. If the overload is likely to be of short duration, the motor may remain connected to the line with field excitation removed. It will continue to operate as an induction motor, and if the load drops to a sufficiently low value, it may resynchronize. During such operation as an induction motor, care must be taken to protect the squirrel cage winding on the rotor against overheating, and the motor must be disconnected from the line if the squirrel cage winding reaches its permissible temperature rise.

The pull-out torque of a given motor varies with its field excitation. It increases as the field current is increased. The lower curve of Fig. 97 is the steady state pull-out characteristic of a typical synchronous motor, plotted versus field current. Pull-out torque, as given by that curve, is obtained when the load torque is raised gradually until the point is reached at which the motor loses synchronism.

If an overload is applied suddenly to the motor, it can develop a much higher pull-out torque for a short period of time than the steady state pull-out characteristic indicates. *The so-called transient pull-out torque, that is, the maximum instantaneous torque peak the motor can stand without pulling out of step,* is given by the upper curve in Fig. 97. This transient pull-out torque is caused by the inherent sluggishness of the magnetic circuit of the motor. If the load is increased, the demagnetizing action of the stator load current reduces the flux linkages between the stator and the rotor and causes an increase in the angle of displacement between rotor and stator poles. This action cannot take place instantly. Thus the motor develops a higher pull-out torque than the steady state value, until the demagnetizing action of the stator load current has taken effect. The time involved is about a second or a substantial fraction thereof.

If a motor is subjected to suddenly applied fluctuating overloads, it can carry higher overloads than its steady state pull-out characteristic indicates, if the excitation system permits a rapid increase in field current upon the occurrence of an overload. Quick response exciters, such as the amplidyne, are well suited for such applications.

Power Factor Correction

Stator current and power factor of a synchronous motor vary with field excitation. In Fig. 98 the stator current is plotted versus field current for various amounts of load. Because of their peculiar shape, these curves are called V-curves. For a given load, the stator current is minimum and the power factor is unity at a certain field current. If the field current is increased, the power factor is leading. If the field current is decreased, the power factor is lagging. The broken line connects points of unity power factor. In the region to the right, the power factor is leading, and to the left it is lagging.

Standard synchronous motors are usually rated to carry full load at unity power factor or at 0.8 leading power factor. Synchronous motors can be used not only to carry a useful load but also at the same time to generate reactive kva which improves the power factor of the supply system. If the mechanical load on the motor is not constant, the excitation system can be arranged so that field current varies as a function of load and so that the motor either operates over its load range at a constant power factor or supplies constant reactive power to the supply system.

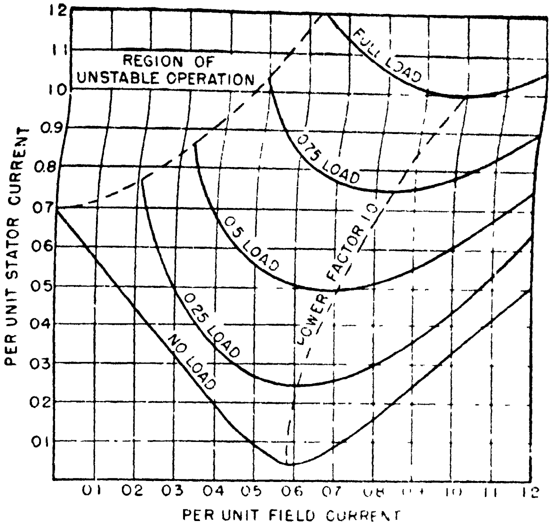


FIG. 98. V-curves of a typical synchronous motor rated at 1.0 power factor.

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CHAPTER 4

DIRECT-CURRENT CONTACTORS AND RELAYS

NEMA defines a magnetic contactor as a device, actuated by electromagnetic means, for establishing and interrupting an electric power circuit repeatedly. Principal parts of a contactor are the electromagnet, the contacts, and, if required, the blowout structure. As compared with circuit breakers, contactors have only a moderate interrupting capacity since protection of a power system is not the principal consideration in their design. Contactors are designed to handle motor circuits and their contingent overloads, and they must be able to perform a large number of closing and opening operations without attendance. Whereas a circuit breaker must be prepared to interrupt high short-circuit currents a few times during its lifetime, a contactor interrupts its rated current and moderate overloads a great many times. The life of a circuit breaker is measured in terms of thousands of operations, whereas the life of a contactor is measured in terms of millions of operations.

A relay is defined by NEMA as a device operated by a variation in the characteristics of one electric circuit to effect the operation of other devices in the same or in another electric circuit. Relays may be designed to respond to voltage, current, speed, direction of current, and the like. They may be used to obtain a specific performance, such as sequencing, or to produce a time delay. Depending on the application, the primary consideration in the design of a relay may be accuracy of response, ease of adjustment, long life, or a combination of all three. Control relays differ from switchgear relays in that the requirements of accuracy of their response are not quite so exacting, but greater emphasis is placed on ability to operate many times in rapid succession and to perform many operations without any attendance.

Advantages of Magnetic Control

The principal advantages of magnetic control versus manual control are greater flexibility, greater safety, and convenience to the operator.

If manual control is used for a large motor, the physical location of the controller presents a problem. Locating the controller close to the motor permits the shortest runs of heavy power leads. However, this may be a very poor location from the operator's point of view, making it difficult to observe and operate the machine. Placing the controller away from the motor requires long runs of heavy power cables. Magnetic control, on the other hand, permits installing the power contactors close to the motor, whereas the actuating control devices, requiring only small-size control wiring, can be located away from the motor in a position most convenient to the operator.

Many industrial applications, such as rolling mills, processing lines, movable bridges, and roller hearth furnaces, involve the use of a number of motors that must be controlled by a single operator at a work station, from which he can observe and supervise all parts of the installations With magnetic control, a large number of pilot devices can be consolidated in a small space, greatly reducing the physical and mental effort necessary to operate a large and complicated piece of machinery. With magnetic control it is easy to interlock various operations of a multi-motor drive so that different motions can be performed only in their proper sequence, preventing false starts with their inherent danger to life and limbs of the operator.

Many industrial processes require automatic operation of motors as a function of quantities measured by delicate instruments. The small amount of control power required to actuate contactors can be handled by pilot devices responsive to operating signals, whereas it would be impossible for pilot devices to control motor circuits directly. As an example, consider an electric furnace. A delicate temperature-sensitive instrument, with the help of contactors, maintains furnace temperature much more accurately than manual control ever could.

When magnetic control is used, the operator is physically remote from power circuits and contacts which open power arcs. This distance minimizes the danger of operators coming in accidental contact with live parts or being exposed to power arcs and flashes. When high-voltage motors are started and stopped frequently, magnetic contactors are the only means to control such motors without danger to the operating personnel.

An important advantage of magnetic control is the ease with which the performance of the motor and the driven machinery can be adjusted and maintained, independent of the skill of the operator. Current and torque peaks can be limited, thus avoiding unnecessary wear and tear which may be caused by a manual controller in the hands of an unskilled operator. The result is a reduction in maintenance required on both the motor and the controller.

Shunt Contactors [1]

Shown in Fig 99 is a typical single-pole contactor, representative of d-c contactors of 100-ampere and higher rating. As the great majority of applications call for single-pole contactors on d-c motors, the single-pole form is most widely used. If an application requires several poles to operate simultaneously, two or more single-pole contactors, operating as a unit, are used.

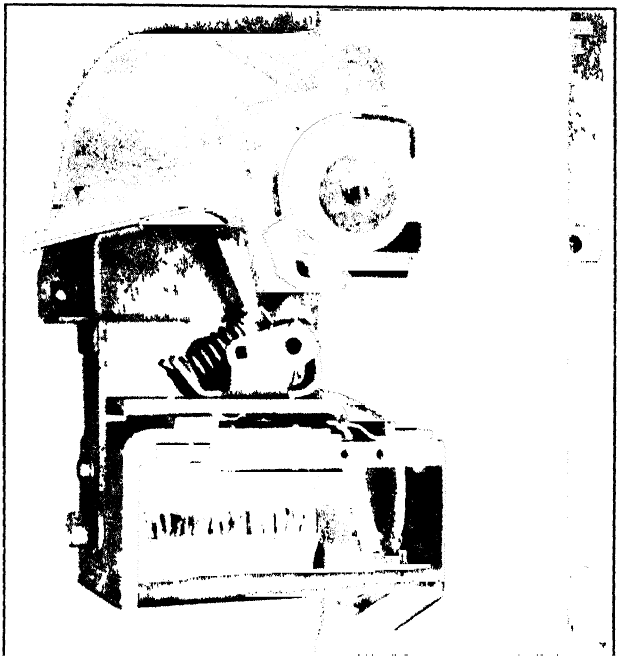


FIG. 99. Typical single-pole, d-c mill type contactor

The magnetic circuit of the contactor consists of a stationary frame and a moving armature. The material is soft steel with high permeability and low coercive force. When the coil is excited, the armature is attracted by the part of the frame which forms the core of the coil. The magnetic pull must be sufficient to close the armature against contact spring pressure. When the coil is de-energized, the armature drops open. To prevent the armature from being held in by residual magnetism, a shim of non-magnetic material is provided in the magnetic circuit.

The coil consists of a large number of turns of fine wire. Each coil is rated in terms of voltage of the control circuit for which the coil is designed. Coil current equals coil voltage, divided by coil resistance. The resultant ampere-turns produce sufficient magnetic pull to close the armature. AIEE Standards for Industrial Control Apparatus specify that coils must perform satisfactorily between 80 and 120 per cent of rated control voltage. This specification means that with 120 per cent of rated control voltage applied, coils must not overheat when continuously energized. The permissible temperature rise is between 50 and 85 C, by thermometer, or between 70 and 105 C by resistance method, depending on the character of the organic and inorganic material in the coil insulation. When coils are hot, their resistance increases, and with 80 per cent of rated control voltage applied, they must develop sufficient pull to close the armature. To compensate for the rise in coil resistance when hot (allowing for a rise of 27 per cent in coil resistance), contactors are tested with cold coils at 63 per cent of rated voltage.

A contactor coil possesses not only resistance but also a considerable amount of inductance. The behavior of a contactor coil, when voltage is applied to it or when the coil current is interrupted, is similar to the behavior of the shunt field of a d-c motor. When the coil current of a contactor is interrupted, the voltage across the coil terminals may rise to as much as fifteen times normal control voltage. This possibility must be considered in the design of the coil insulation. The effect of coil inductance on closing and opening performance of a contactor is discussed later in this chapter.

The armature carries the movable contact tip which, when the armature is closed, makes a butt contact with the stationary contact tip, which is supported from the panel or from the stationary portion of the contactor. To insure good contact between stationary and movable contact tips, the movable contact is backed by a spring, and the armature must have sufficient pull to close the contact tips and to compress the contact spring. The movement of the armature from the position at which the contacts just touch to the position at which the contact spring is fully compressed would cause the contacts to overlap if the stationary contact did not stop the movable contact. This extra motion, measured at the tips, is called the *wipe*. Contact spring pressure and wipe are specific design characteristics of each type of contactor. They should be checked periodically in service to insure that contactors perform satisfactorily.

Contact tips are shaped so that, upon closing, they touch near the middle or near their upper ends. While the contact spring is compressed, they go through a sliding and rolling motion, and final contact is made near the base of the tips, insuring that the contacts clean themselves every time they close. When the contact tips first touch, there may be a slight amount of bouncing with a tendency for tiny arcs to form, which may cause welding. The rolling motion serves to break up any spots which may have fused together. When the contacts open, they go through a reverse motion. Thus the lower contact portion only carries current, whereas the upper contact portion interrupts current and takes the burning which accompanies arcing, thereby keeping the current-carrying portion of the contacts comparatively clean. On large contactors two separate sets of contact tips are often provided. One set, which closes last and opens first, only carries current. The other set, which closes first and opens last, interrupts the current and takes the arcing.

The most widely used contact material is copper, which is economical and has satisfactory resistance to arc erosion. Copper however, has one important disadvantage as a contact material; its oxide is an insulator. If it forms, it increases contact resistance and causes overheating. Contactors which stay closed for long periods of time are equipped with contacts having silver inserts welded or brazed to the copper tips, for carrying current. Silver oxide is a conductor, and it is soon reduced to silver by any heating that is due to its presence. However, silver has poorer mechanical wearing qualities than copper and less resistance to arc erosion. Silver is not suitable for contacts which open frequently and are subjected to considerable arcing.

When contactors have to close frequently on high inrush currents, special alloy tips are used at times to obtain better non-welding qualities. The base metal is silver, to which various other metals are added. Because carbon possesses the best non-welding qualities of all contact materials, it was used extensively in the past as tip material. However, its use has decreased greatly because carbon contacts are mechanically weak and subject to breakage. Occasionally carbon contacts are used where welding must be avoided under all circumstances, to prevent possible loss of life. Sintered materials containing carbides of silver or tungsten are sometimes used to increase tip life on contactors subjected to frequent arc interruptions. Because of their greater hardness and arc resistance, sintered contact tips last longer than either copper or silver tips. Although alloy or sintered contacts are superior in many respects to either copper or plain silver, their use is not widespread because of their relatively high cost.

Coordination of the design of the magnet and of the contacts is important to minimize the danger of welding of the contact tips. With the armature open, there is a large air gap in the magnetic circuit, and the coil must develop sufficient pull to accelerate the armature. As the armature moves, the air gap is reduced, and the magnetic pull increases steadily. When the contacts touch, the load on the magnet increases suddenly. The magnet must have sufficient pull to compress the contact spring without hesitation and without tendency of the movable contact to bounce open. Even a very small amount of bouncing may cause an arc to form, and molten particles on the movable and stationary contacts may fuse together. Once the contacts touch, they must not part again during the closing operation. Likewise, when the coil is de-energized, the contactor armature must drop open without hesitating at the point at which the contact spring is unloaded, that is, when the contacts *unwipe*. Sluggishness of the armature with the contacts barely touching, with no pressure behind them, may cause the tips to fuse together.

Interruption of d-c arcs is more difficult than the interruption of a-c arcs because the current does not pass through zero and a low voltage is able to maintain an arc of considerable length. In order to extinguish the arc formed upon the opening of the contact tips, it may be artificially elongated by a magnetic blowout field which is produced by a copper coil, wound on a soft steel or iron core. This coil may either be connected to the control source (shunt blowout) or it may carry the load current of the contactor (series blowout). The core is connected to blowout shields of magnetic material, located so that a magnetic flux is set up by the load current, the direction of which is perpendicular to the direction of contact movement. When the contacts part, the flux, interacting with the load current, exerts a force on the arc which causes it to move up and away from the contact tips, until it is so elongated that line voltage no longer is able to sustain the arc, which then extinguishes. Arcing horns are arranged in such a way that the arc moves from the contact tips onto the arcing horns, thus relieving the contact tips of some of the burning associated with the arcing. Arc chutes, made of non-conducting and heat-resisting material, confine the arc and prevent its being blown against structural parts of the contactor. Restrictions in the arc chute are beneficial since they cool the arc and thus assist in extinguishing it.

Motor loads are moderately inductive. Standard contactors have their series blowouts designed so that the coil provides the correct number of ampere-turns to extinguish motor load current arcs, and the blowout coil carrying capacity is commensurate with the contactor rating. If highly inductive circuits are to be interrupted, such as shunt fields or shunt brake coils, best results are obtained if a contactor is selected, the blowout coil rating of which is three to four times the current to be interrupted. The series blowout field, which obtains good arc interruption on a motor circuit, would interrupt an inductive circuit so rapidly that the arc is likely to become elongated excessively, touching structural parts outside the arc chute. Using a contactor whose blowout coil rating is higher than the current to be interrupted reduces the blowout field strength below its normal value and results in slower elongation and extinction of the arc, which is preferable on field circuits and the like. When contactors are equipped with shunt blowout coils, which are connected to a constant potential source, the flux of the blowout coil is independent of load current, and the ampere-turns can be selected so as to obtain the best performance for a given load circuit.

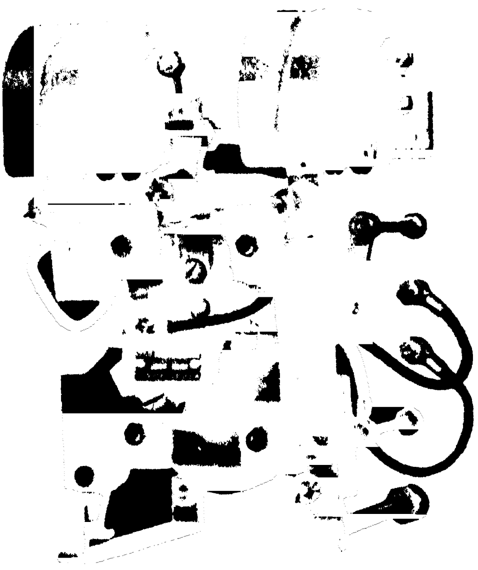


FIG. 100. Small double-pole d-c contactor with electrical interlocks.

Small contactors, of less than 100-ampere rating, are often built as multi-pole contactors. Figure 100 is a view of a typical small contactor, having two poles with blowouts for power circuits and several auxiliary poles without blowouts, which are used for control circuits.

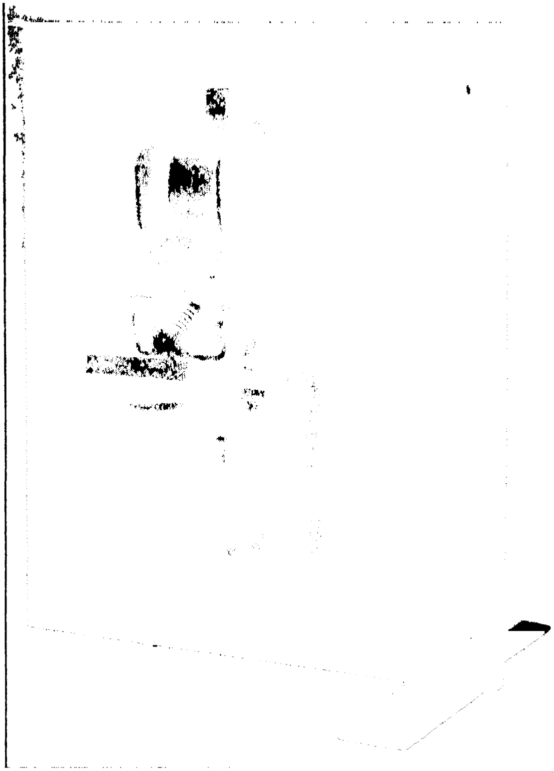


FIG. 101. Normally closed d-c contactor with arc chute removed.

Many control applications require contactors which are closed by spring action when the coil is de-energized, and open when the coil is energized. Such contactors are called normally closed. On small contactors, such as shown in Fig. 100, normally closed poles, with or without blowout, are assembled on the same armature as the normally open poles. In the larger sizes, above 100 amperes, this is not practicable, and normally closed contactors are built as single-pole units. A typical example is shown in Fig. 101.

Rating of Contactors

The rating of a contactor is determined by its ability to carry its rated current for 8 hours (which is equivalent to continuous duty) without overheating of any of its parts. The 8-hour period was selected because contactors attain their ultimate temperature rise within that time. NEMA permits a temperature rise of 65 C for solid contacts. A contactor, when applied to motor loads within its rating, must be able to interrupt power arcs occurring during regular motor duty, including moderate overloads, without undue wear of the current-carrying parts and without failure to interrupt the arcs. It is not customary to assign an interrupting rating to contactors. However, d-c contactors designed for circuit voltages of 600 volts or less usually have an interrupting capacity of ten times their normal current rating, and a one-second current-carrying capacity of fifteen times their normal current rating.

TABLE 4

NEMA Continuous D-C Contactor Ratings

Open 8-Hour Rating in Amperes	*Corresponding Horsepower Rating at*		
	115 Volts	*230 Volts*	*550 Volts*
25	3	5	
50	5	10	20
100	10	25	50
150	20	40	75
300	40	75	150
600	75	150	300

TABLE 5

NEMA Mill and Crane D-C Contactor Ratings

8-Hour Rating in Amperes	*Mill Rating in Amperes*	*Mill Rating Horsepower at 230 Volts*
100	133	35
150	200	55
300	400	110
600	800	225
900	1200	330
1350	1800	500

NEMA has standardized certain contactor sizes on the basis of their 8-hour rating, when installed in the open. In Table 4 standard ampere ratings are listed, together with corresponding motor sizes in horsepower at various line voltages.

On many applications motors are not selected on the basis of their continuous rating, but they are applied to duty cycle drives on the basis of their intermittent or short-time rating. For steel mill auxiliaries and material-handling equipment, such as cranes, intermittently rated motors are generally used. To coordinate motors and control for such applications, NEMA has established intermittent or mill ratings for contactors of 100-ampere size and larger. The intermittent rating of a given-size contactor is arbitrarily set at 1⅓ times its continuous rating. In Table 5 the standard mill ratings of contactors and the corresponding motor horsepower ratings are listed.

Interlocks

In many control systems it is necessary to close a control circuit when a power contactor closes. Likewise, it may be necessary to open or lock out a control circuit when a power contactor closes. For such purposes, auxiliary contacts, called electrical interlocks, are connected to the contactor armature. They may be normally open, that is, they are open when the contactor is open and they are closed when the contactor closes. Conversely, normally closed interlocks are closed when the contactor is dropped out and open when the contactor is energized. The contactor shown in Fig. 3 is equipped with a normally open interlock. Likewise, the contactor of Fig. 100 has a number of electrical interlocks which carry no blowouts. Normally open interlocks are located at the top center and the bottom left of the contactor armature, and a normally closed interlock is at the bottom right.

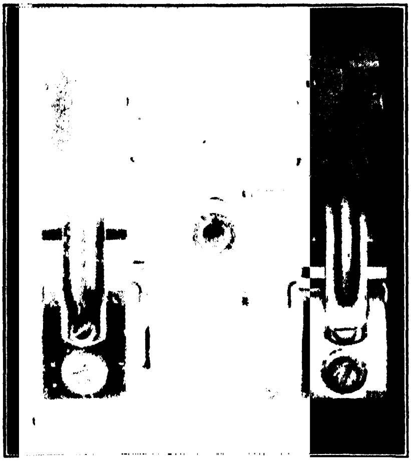


FIG. 102. Pair of d-c contactors, mechanically interlocked.

Inadvertent simultaneous closing of several contactors, especially reversing contactors, must often be prevented to avoid short-circuiting of power lines. Mechanical interlocks are then used between pairs of contactors. Shown in Fig. 102 is a pair of d-c contactors with a rocker type mechanical interlock between them. As long as one contactor is closed, the second contactor is locked out mechanically and prevented from closing, even though its coil may be energized.

The equivalent effect can be obtained by the use of holding coils. The contactor shown in Fig. 100 has two magnet coils. The top coil is the operating coil which, when energized, causes the contactor to close. The bottom coil is the holding coil which, when energized, locks the contactor open. In order to interlock a pair of contactors, the operating coil of one contactor is connected in series with the holding coil of the second contactor. Suppose that the first contactor is closed. The holding coil of the second contactor is energized, and the armature is held against the core of the holding coil. If the operating coil is then energized, its magnetic pull is insufficient to overcome the pull of the holding coil. Thus the contactor is prevented from closing.

Relaying Contactors and Control Relays

Many controllers used in connection with processing machines and multi-motor drives require a considerable amount of interlocking and

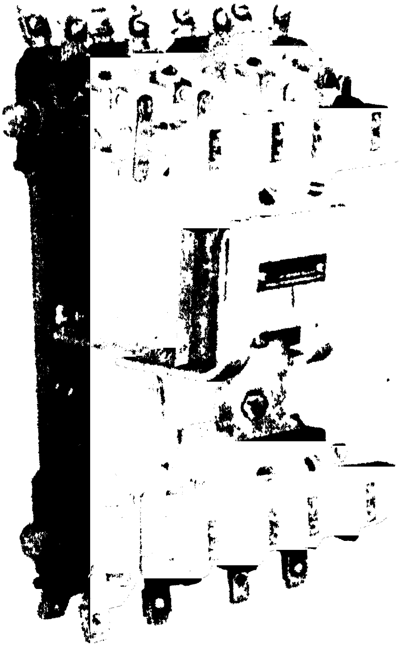


Fig. 103. Multi-circuit control relay with silver button contacts.

sequencing. Relays are then required which do not respond to any particular electric or mechanical quantity of the drive, but simply open or close their contacts, depending on whether or not the coil of the relay is energized. Small power contactors of the type as shown in Fig. 100 are often used for such purposes, and blowouts and arc chutes are omitted because the small amount of power present in control circuits does not require any special provision for arc interruption.

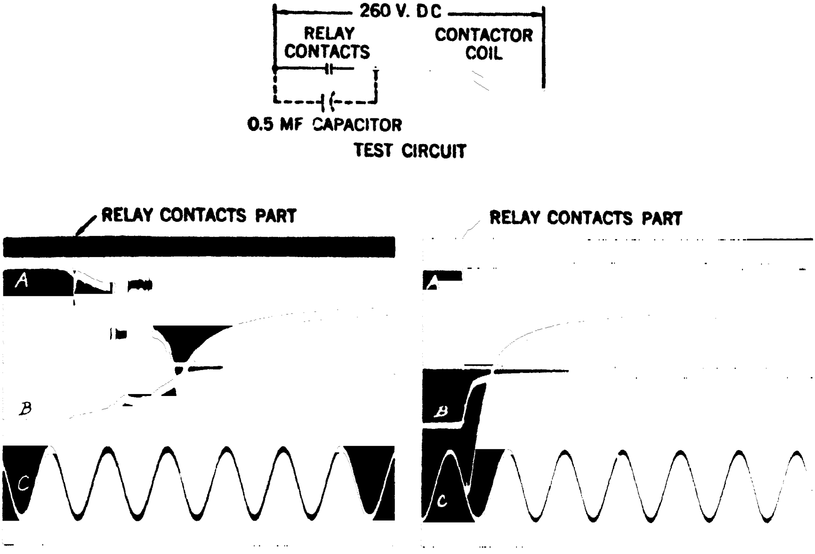
Where large numbers of contacts are needed on one relay, special multi-circuit control relays are available. A typical example is the relay shown in Fig. 103. At the top of the armature are the normally open contacts, and at the bottom are the normally closed contacts. The contact tips consist of silver buttons, and each contact introduces two breaks in the circuit. Contact spring pressure is comparatively high and contact resistance is low. Such relays are particularly suitable for use in closed cycle control systems, in which contacts often carry only a few milliamperes and the error introduced by high contact resistance may seriously affect the accuracy and response of the control system.

Effect of Contactor Coil Inductance

Any inductance has the ability to store energy. When the circuit to the coil of a contactor is interrupted, for instance by a relay contact, the energy stored in the magnetic circuit tries to discharge through the arc forming across the relay contacts. As long as the coil current is low and the relay contacts have a sufficiently large gap, the arc is not sustained for any length of time, and the relay contacts break the coil current clean. If, however, the coil current is of the order of one ampere or more, an arc of considerable duration may form across relay contacts, and they may even fail to break the arc. This condition can be remedied by connecting a small capacitor of 0.5 to 1 microfarad capacity across the relay contacts or across the contactor coil. The capacitor provides a discharge circuit for the magnetic energy stored in the contactor coil and reduces the arcing of the relay contacts effectively.

It is illustrated by the oscillograms of Fig. 104. The left-hand oscillogram was taken without a capacitor. The relay contacts were barely able to interrupt the contactor coil current. The arc duration on the relay contacts was 34 milliseconds. The right-hand oscillogram was taken with the same test circuit, except that a 0.5 microfarad capacitor was connected in parallel with the relay contact. The arc duration was reduced to 2.6 milliseconds. The voltage rise across the relay contacts during current interruption was increased, but this increase did not prevent the relay contact from breaking the contactor coil current clean.

The same effect can be obtained by connecting the capacitor in parallel with the contactor coil. This method has an important advantage. An internal short circuit of a capacitor in parallel with the relay contact might cause inadvertent closing of the contactor and thus a false motor start. Failure of a capacitor in parallel with the contactor coil would only cause the control power circuit to be short-circuited and the control fuses to blow.



NO CAPACITOR ACROSS RELAY CONTACTS WITH CAPACITOR ACROSS RELAY CONTACTS

FIG. 104. Interruption of d-c arc without and with capacitor. Trace *A*: Voltage across relay contacts. Trace *B*: Current through relay contacts. Trace *C*: 60-cycle timing wave.

When voltage is applied to a contactor coil, the coil current cannot rise immediately to its ultimate value as determined by the coil resistance. The current builds up gradually according to an exponential curve, as explained in Chapter 2 in connection with motor shunt fields. The speed of current build-up is determined by the ratio of inductance to resistance of the coil. This relationship means that when the contactor coil is energized, a definite period of time elapses before the magnetic pull builds up to a sufficient magnitude to cause the armature to close. For small- and medium-size contactors, up to 150-ampere rating, the contactor closing time is of the order of 0.1 second or less. Up to 600-ampere rating, the closing time may be as high as 0.2 second. While such closing times are not a serious handicap, they must be taken into consideration when analyzing control operation of fast-duty cycles.

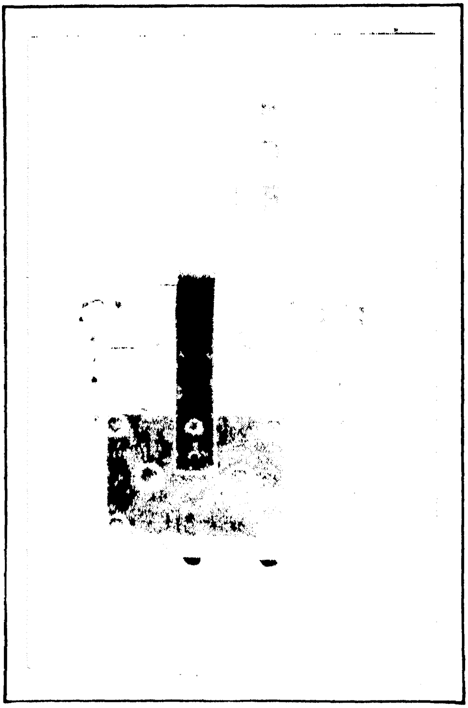
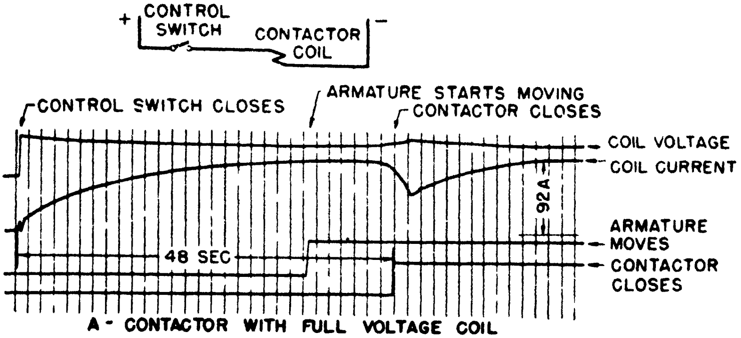


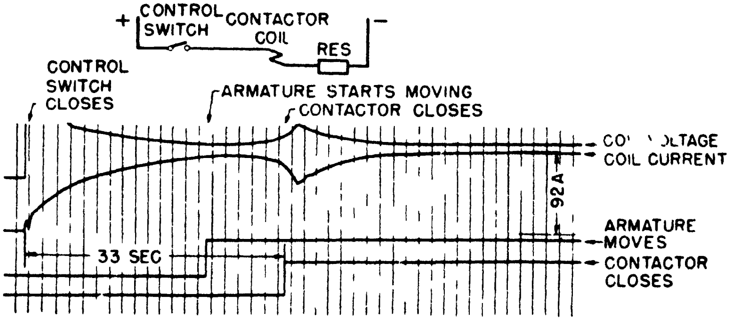
FIG. 105 Single-pole d-c contactor, rated 2500 amperes.

Contactor closing time may become a serious matter when large contactors, rated 1000 amperes or more, are used. Such a contactor is illustrated in Fig. 105. The magnetic circuit has a great mass, and two large coils are required to close the contactor. Coil inductance is high as compared with coil resistance. In Fig. 106 oscillograms are shown taken during tests made on a 1500-ampere contactor. The upper oscillogram *A* shows the results of a closing test with coils rated for full control circuit voltage. The coil current rises very slowly. Contactor closing time is 0.48 second. The dip in the coil current trace is caused by the sudden increase in coil inductance when the armature is closing.

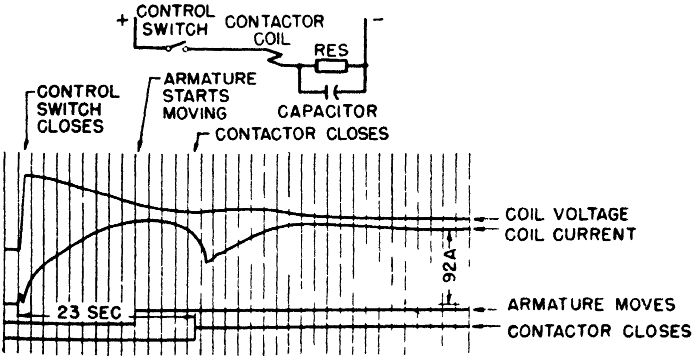
The time required for the contactor to close can be cut down by reducing the time required for the coil current to build up to a



A - CONTACTOR WITH FULL VOLTAGE COIL



B - CONTACTOR WITH HALF VOLTAGE COIL



C - CONTACTOR WITH HALF VOLTAGE COIL AND CAPACITOR

FIG. 106. Effect of coil selection on closing time of d-c contactor.

value sufficient to move the armature. It can be done by decreasing the ratio of inductance to resistance by using coils rated for one half control circuit voltage and connecting a resistor in series with them. The middle oscillogram *B* shows the result of a closing test with half voltage coils. Coil current builds up faster, and contactor closing time is reduced to 0.33 second. A further reduction in contactor closing time can be obtained by using partial voltage coils and connecting a capacitor in parallel with the series resistor. The lower oscillogram *C* was taken with half voltage coils and a capacitor of 600 microfarads in parallel with the series resistor. The capacitor admits a high initial inrush current through the coil, which results in a further increase in the speed of current build-up. Contactor closing time is reduced to 0.23 second.

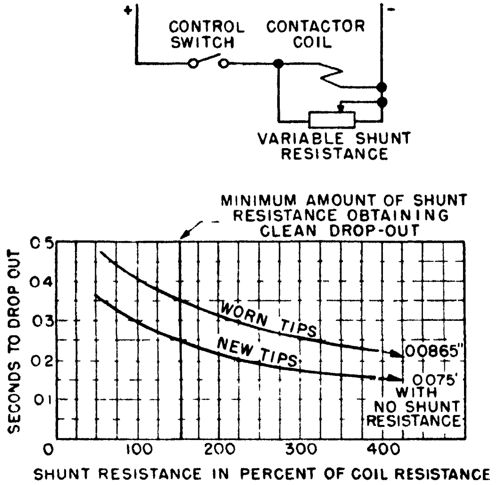


FIG. 107. Effect of shunt resistance on drop-out time of d-c contactor.

Coil inductance can be utilized to obtain a slight delay in the opening time of a contactor, which at times is desirable in order to overlap contactors in a control sequence. Connecting resistance in parallel with the contactor coil provides a discharge path. When the coil is de-energized by opening the control circuit, the coil current decays according to an exponential function. The time constant varies inversely with the amount of resistance in shunt with the contactor coil. Slow decay of coil current corresponds to slow decay of flux, which delays the opening of the contactor armature. In Fig. 107 the results of opening tests on a single-pole contactor are plotted. Care must be taken not to use too low an amount of coil shunting resistance. If the flux decay is too slow, the armature hesitates at the point at which the contact spring is unloaded, with the resultant danger of freezing the contact tips.

Contactor opening time is influenced by the condition of the contact tips. With worn tips, wipe and contact spring pressure are reduced. When the coil current is interrupted, the flux must decay to a lower value before the contacts start to move and the acceleration imparted to the armature by the contact springs is reduced, thus resulting in slower drop-out. The upper curve in Fig. 107 indicates the increase in contactor opening time with tips worn to one half their original thickness, as compared with new tips.

Magnetic Time Delay Relays

Gradual decay of flux provides a simple way to obtain controlled time delay drop-out. Shown in Fig. 108 is a relay which obtains time delays up to 1.5 seconds. The magnetic circuit consists of soft steel and the armature gap is proportioned so that, with the armature open, coil inductance is low. When the coil is energized, its coil current builds up rapidly and the armature closes fast. Inside the coil there is a copper jacket which is slipped over the core. This copper jacket acts like a single-turn short-circuited coil. When the relay

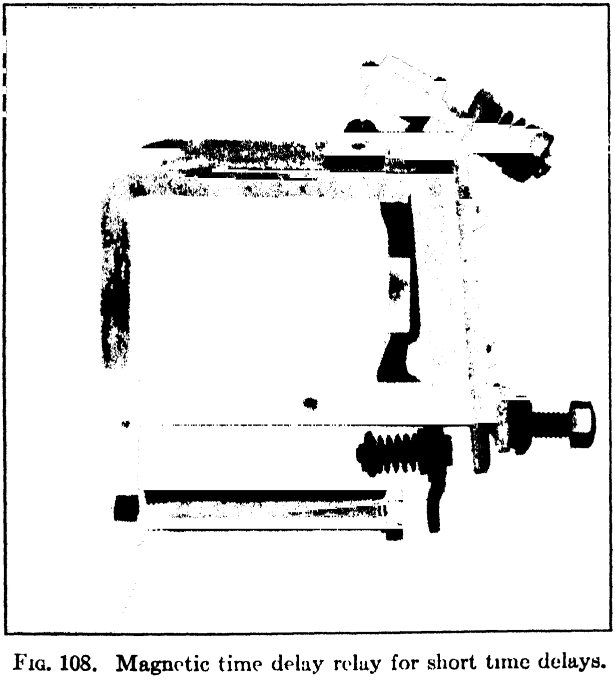


FIG. 108. Magnetic time delay relay for short time delays.

coil is de-energized, the decay of flux induces a voltage in the copper jacket, and current flows in the copper jacket in a direction to maintain flux. The decay of flux is delayed, resulting in delayed opening of the relay armature.

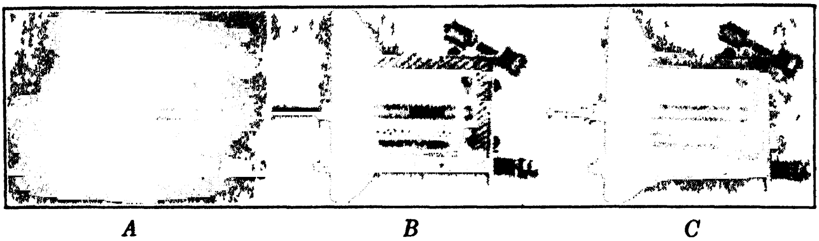


FIG. 109 Time delay drop-out of d-c magnetic time delay relay.

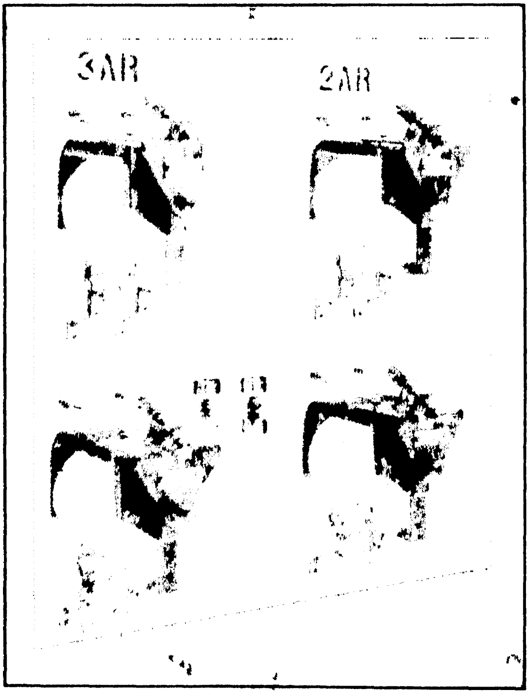


FIG. 110 Magnetic time delay relays for long-time delays.

The effect of the copper jacket is illustrated in Fig. 109. The left-hand picture *A* shows the condition which exists after the coil has been connected to the control source for some time. Current flows in the coil, but no current flows in the copper jacket. Magnetic flux is at normal strength. The relay armature is closed. The middle picture *B* shows what happens after the coil circuit has been interrupted. No current flows in the coil, but current flows in the copper jacket. The flux is decreasing at a rate just sufficient to maintain current in the jacket, and the relay armature is still closed. After a further interval of time, the condition exists which is shown in the right-hand picture *C*. The current in the copper jacket and the flux have decayed to such a low value that the armature cannot be held in the closed position.

The same effect of time delay drop-out can be obtained without a copper jacket if the relay is de-energized by short-circuiting its coil The coil then acts as its own discharge resistor, and coil current and flux decay gradually. Longer time delays, up to 7 seconds, can be obtained with somewhat larger relays having a larger coil and greater mass in their magnetic circuit. Several such relays, mounted on a control panel, are shown in Fig. 110.

Magnetic time delay drop-out relays as described above are used for timing control sequences and for timing acceleration. The amount of time delay can be adjusted by varying the pressure of the armature spring and by using non-magnetic shims of different thickness between the armature and the magnet core.

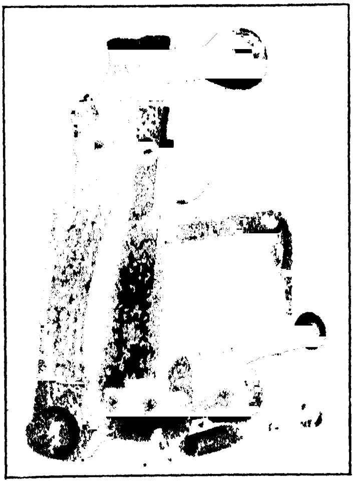


FIG. 111. Accelerating contactor with inherent time delay drop-out.

Definite Time Accelerating Contactors

The function of an accelerating contactor and a definite time relay can be combined in one device. The accelerating contactor of Fig. 111 has a frame similar to a magnetic time delay relay. The coil is copper jacketed. The armature carries a heavy contact tip which closes when the armature is dropped out. Such contactors are used to short-circuit sections of motor-starting resistors. This type of contactor is used only to close a circuit as it is not suited for interruption of current. A time delay of 1 to 1½ seconds can be obtained.

Time Delay Relays with Capacitor Discharge [2, 3]

With the perfection of electrolytic capacitors for low voltages, it has become possible to obtain capacitors of several hundred microfarads in sufficiently small units to make them suitable for use in control circuits. A capacitor has the ability to store energy. The energy stored in a capacitor is

$$E = \frac{CV^2 10^{-6}}{2} \tag{55}$$ ●

where E = stored energy in watt seconds,
C = capacitance in microfarads,
V = applied voltage in volts.

This stored energy can be used to obtain time delay drop-out of a relay by discharging the capacitor through the coil of the relay.

Consider the circuit shown in upper sketch A of Fig. 112. A capacitor, in series with a resistor, is connected in parallel with the coil of the relay. In this circuit

R = total resistance in ohms (coil plus external resistance),
L = inductance of relay coil in henrys,
C = capacitance of capacitor in microfarads.

If a voltage is applied to this circuit, or if voltage is removed from it, a transient current flows which is superimposed to the steady state current. The nature of the transient current may or may not be oscillatory, depending on the relation between R^2 and quotient L/C. The transient current is not oscillatory, if

$$R^2 > \frac{4L}{C10^{-6}} \tag{56}$$ ●

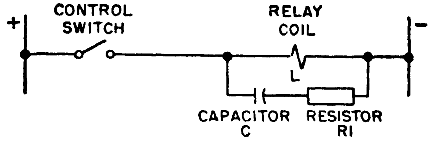
As long as this condition is satisfied, the transient current through the capacitor follows an exponential curve.

If the control switch in sketch A is closed and voltage V is applied to the relay coil, the charging current i through the capacitor, as a function of time t, is given by the equation

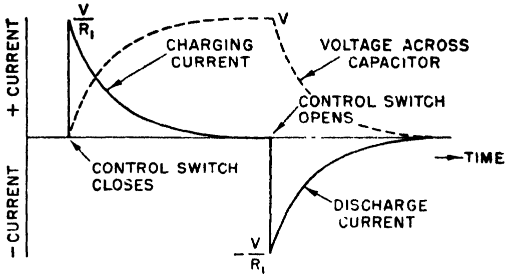
$$i = \frac{V}{R_1} \epsilon^{-t/RC10^{-6}} \tag{57}$$ ●

This charging current is plotted in sketch B of Fig. 112. Its initial peak value is determined by applied voltage divided by resistance in series with the capacitor. Decay of the current is determined by *time constant $RC10^{-6}$. The broken curve is the voltage across the capacitor, which is a measure of energy stored in the capacitor as a function of time.*

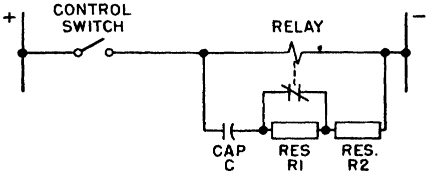
When the control switch is opened, a discharge current flows from the capacitor through the relay coil. To plot discharge current i as



A-CAPACITOR TIMING CIRCUIT



B-CHARGING AND DISCHARGE CURRENT OF CAPACITOR



C-CAPACITOR TIMING CIRCUIT FOR LONG TIME DELAYS

FIG. 112. Time delay drop-out by capacitor discharge.

a function of time, it is permissible to neglect coil inductance L. As coil resistance is usually much smaller than resistance R_1, it is also permissible to neglect coil resistance. The equation for the discharge current becomes

$$i = -\frac{V}{R_1}\epsilon^{-t/R_1C10^{-6}} \qquad (58)$$

The discharge current is of equal magnitude but opposite direction from the charging current. The discharge current holds the relay armature closed until it has decayed to a sufficiently low value to permit the relay armature to open.

The time required for the discharge current to decay is increased by increasing resistance R_1. However, increasing R_1 decreases the initial discharge current peak. Knowing the current at which the relay drops out, a combination of R_1 and C can be determined which obtains the desired drop-out time after the opening of the control switch. After such a calculation, the chosen amount of C must be checked to make certain that $4L/C10^{-6}$ is smaller than R_1^2.

When the circuit in accordance with sketch A is used, it must be considered that it takes as long a time to build up the charge on the capacitor to its full value as it takes the discharge current to decay to zero. Full time delay on drop-out can be obtained only if sufficient time has been allowed for the capacitor to be fully charged before the control switch is opened again. When long time delays are required, say 30 seconds or more, the control sequence may not permit such a long time to charge the capacitor. The circuit shown in sketch C of Fig. 112 overcomes this difficulty. The resistance in series with the capacitor is divided into two sections, R_1 and R_2. The total resistance $R_1 + R_2$ is chosen large enough to obtain the desired time delay on relay drop-out. R_2 is made small but of sufficient magnitude so that the initial capacitor charging current does not damage the control switch contacts. The remaining resistance R_1 is short-circuited by a normally closed contact of the relay. When the control switch is closed, high current flows through the capacitor and charges it fast. When the relay closes, additional resistance is inserted, after the capacitor has already been charged very nearly to its ultimate charge. Thus a substantial portion of the calculated time delay is obtained if the control switch is opened very soon after the relay has picked up.

Voltage and Current Relays

Many control applications require relays that respond to either voltage or current in order to initiate a control sequence as a function of circuit conditions. For instance, the emf of a d-c motor is a measure of motor speed, and so is the voltage generated by a tachometer generator. A relay which opens or closes at a certain voltage can be used to furnish a control impulse as a function of speed. A current relay, closing or opening as a function of armature current of a motor, may initiate a control sequence as a function of motor load.

As far as the relay is concerned, the closing of its armature is governed by the magnitude of its flux, which in turn is determined by the ampere-turns of the relay coil. The same relay may be used either as a voltage or as a current responsive relay, by placing either a high turn, low current, or a low turn, high current coil on its core.

The time delay relay of Fig. 108 can be used readily as a voltage or current relay by omitting the copper jacket, which eliminates the time delay feature. By varying armature gap and armature spring pressure, pick-up and drop-out of the relay can be adjusted over a wide range. There is one limitation. As the magnetic circuit through the armature has a large cross section and there is only a small air gap between core and armature when the relay is picked up, the drop-out value is always appreciably lower than the pick-up value. This difference is no disadvantage on many applications, but there are cases in which it is desired to drop out the relay as close as possible to its pick-up value. It can be done by using a relay with a light armature and a magnetic circuit which provides for a substantial air gap when the relay armature is closed. Thus the flux required to close the armature is only slightly greater than the flux required to hold the relay closed. In Fig. 113 a high drop-out relay is shown.

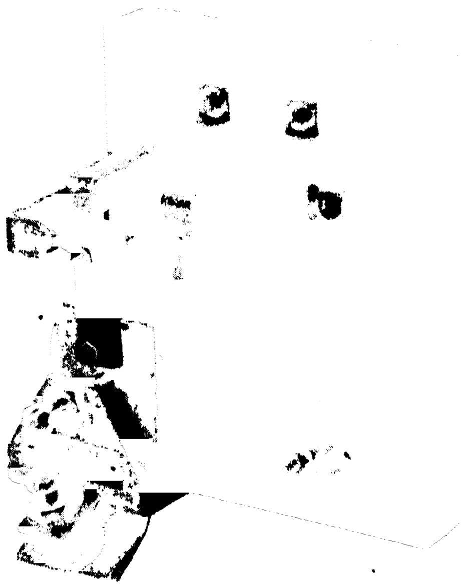


Fig. 113. Voltage relay with high ratio of drop-out to pick-up.

Pneumatic Contactors [4]

When motors larger than 225 hp at 230 volts are used, adjustable-voltage control is generally applied and small contactors, switching field circuits, perform the required control functions. Occasions arise, however, especially in connection with drives installed on moving structures such as car dumpers or ore bridges, when the motor generator sets necessary for adjustable-voltage control cannot be accommodated. Then it is necessary to build *rheostatic* controllers with contactors rated 1500 amperes or higher for switching line and resistor connections. Air-operated contactors offer certain advantages for such applications.

Fig 114 Air-operated contactor, rated 2500 amperes, with arc chute removed

Shown in Fig 114 is an air-operated contactor, rated 2500 amperes. The arc chute is removed, to expose contacts and blowouts. Two insulated side members carry the stationary contact. The movable contact, pivoted to the side member, is actuated by an air cylinder through an insulated piston. A magnet valve, when energized, admits air to the cylinder. The piston closes the contactor and holds it closed against the pressure of a spring. De-energizing the magnet valve cuts off the air supply from the cylinder, and the spring opens the contactor. By inverting the cylinder, a normally closed contactor can be obtained, the contacts of which open when air is admitted to the cylinder and close by spring action.

An air supply with a pressure between 65 and 90 pounds per square inch can be used for operating such contactors. The amount of air required depends on the number of contactors and the frequency of operation. On a recent car dumper installation a 10-cubic-feet-per-minute compressor was found adequate for operating twenty-six 1500-ampere contactors and two 8000-ft-lb air-operated brakes. When an air-operated contactor installation is planned, care must be taken to insure a continuous and reliable air supply. Pneumatic control can operate successfully in the winter time only if the air lines can be kept from freezing.

The advantages of pneumatic contactors, which make their use desirable in sizes of 1500 amperes or above, are:

1. They can be built more compact than magnetic contactors of equal size, thus saving space and weight.
2. They respond fast to control impulses, their closing time being less than 0.1 second with air pressures varying between 60 and 80 pounds per square inch.
3. The control current taken by the magnet valve is less than 0.05 ampere at 230 volts, which greatly relieves the duty on control contacts.

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3. Carroll Stansbury and Theo. B. Hochlm, "Capacitor Relay Timing in Industrial Control," *Transactions AIEE*, February 1940.
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CHAPTER 5

ALTERNATING-CURRENT CONTACTORS AND RELAYS

A-c contactors and relays do not differ basically from d-c devices, except for construction details governed by the nature of a-c-magnetic structures. The principal differences between a-c and d-c devices are found in the magnet and the blowout. Whereas d-c magnets consist of solid steel, a-c magnets are made of thin insulated laminations, to reduce the iron losses due to eddy currents.

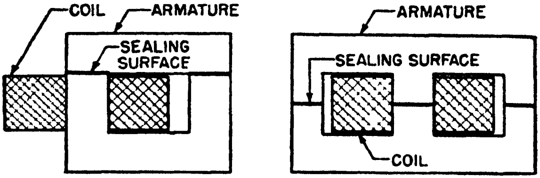
A-c motor controllers require mostly multi-pole contactors, both for motor primary and secondary circuits. Standard a-c contactors are generally designed so that a multiplicity of poles can be accommodated without changing the basic design of a given type of contactors. Up to five poles may be required for pole-changing motors or for auto-transformer starters.

Alternating-Current Magnets

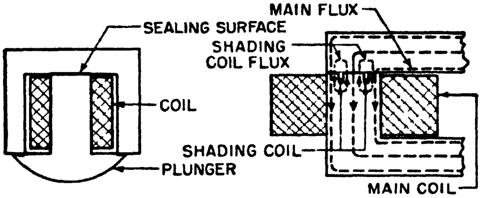
The three types of a-c magnets in general use are illustrated in a schematic manner in Fig. 115. The C magnet resembles a d-c magnet most closely. The stationary core extends through the coil, and the moving armature is entirely outside the coil. The E magnet has a three-legged core. The moving armature extends partly into the coil. The solenoid has a stationary frame, and the core is a movable plunger which is drawn into the coil. The first two types of magnets are generally used on contactors of medium and large size. Solenoids are mostly applied to small contactors and relays.

Whereas the current drawn by a d-c magnet coil is equal to applied control voltage divided by coil resistance, the current of an a-c magnet coil is determined by control voltage and coil impedance. When the magnet is closed, the coil impedance consists largely of reactance, and resistance is only a small fraction of the reactance. Since reactance varies with frequency, coil design must consider both voltage and frequency. The magnetizing coil current varies as the ratio of voltage to frequency, and the same coil can be used for various voltages, provided voltage and frequency vary at the same ratio. For instance, a 110-volt, 25-cycle coil can be used on a 220-volt, 50-cycle control circuit.

When the magnet armature is open, the coil impedance is much smaller than when the armature is closed. The large air gap in the magnetic circuit reduces the coil reactance to a very small value so that the coil impedance is practically equal to the coil resistance. *When a magnet coil is connected to the control circuit, the initial inrush current is much higher than the ultimate coil current.* As the armature moves, the air gap is reduced, and the coil impedance increases because the coil reactance increases. The coil current drops until *magnetizing* current flows when the armature is sealed. Depending on the size and design of the magnet, the ratio of inrush current to magnetizing current varies over quite a range. Solenoids have lowest inrush currents of about five times magnetizing current. E magnets have the highest inrush current, which may be as high as fifteen times magnetizing current. C magnets lie in between.



"C" MAGNET "E" MAGNET



SOLENOID EFFECT OF SHADING COIL

Fig. 115. A-c contactor magnets.

Standard a-c magnet coils are designed so that the contactor closes with control voltage 15 per cent below normal, and the coil does not overheat if control voltage rises 10 per cent above normal. When a controller requires long control leads between the control source and contactor coils, it is necessary to check the voltage drop in the leads to make certain that not less than 85 per cent of normal voltage is available at the coil terminals when inrush current flows. When circuits of great length between control contacts and coils are involved, say 1000 feet or more, the capacitance of the lead wires may become so great as to maintain voltage across the coils of small contactors or relays for a period of time, so that the contactors drop out sluggishly, or not at all, when the control circuit is interrupted. This condition can be remedied by connecting resistance in parallel with each coil, providing a path through which the capacitive charge of the lead wires may discharge.

If inrush current is permitted to flow through a contactor coil for a prolonged period of time, the coil overheats rapidly and burns out. The sealing surfaces of magnets must be kept clean so that the armature closes tightly, without any air gap left in the magnetic circuit; otherwise the current exceeds the rated current of the coil. When mechanical interlocks are used between a-c contactors, control circuits must be designed so as to make it impossible to energize the coil of a contactor that is mechanically locked out.

Solenoids, the most efficient type of magnet, are used mostly on small contactors and relays. On such devices it is desirable to keep inrush and magnetizing currents as low as possible so that pilot devices with limited contact capacity can be used to open and close their coil circuits. Large solenoids become rather bulky, and they do not lend themselves readily to use on larger contactors, for which C and E magnets are preferred. The principal difference in performance between these two forms of magnets is that an E magnet has a higher initial closing pull, but a lower sealing pull, than a C magnet of corresponding size.

With alternating current flowing through a magnet coil, current and flux pass through zero twice every cycle, and the magnet tends to open upon each flux reversal. This condition would result in chattering of the magnet, and larger contactors would become very noisy. Constant vibration would soon cause the laminated magnet structure to fall to pieces. Chattering can be avoided by the use of an auxiliary coil, the so-called shading coil, imbedded in the pole face of the magnet. The action of the shading coil is illustrated by the lower sketch in Fig. 115. A shading coil is a short-circuited loop of conducting material in which alternating current is induced by the main flux. It may either be a punching or be formed of wire. Resistance and reactance of the shading coil are so proportioned that the current induced in it is approximately 120 degrees out of phase with the main flux. Whenever the main flux passes through zero there is an auxiliary flux supplied by the shading coil which holds the armature closed. The breaking of a shading coil becomes immediately noticeable by increased contactor noise. It should be replaced at once to avoid possible damage to the magnet structure.

Low-Voltage Contactors (600 Volts and Less) [1]

There are two commonly used styles of low-voltage a-c contactors. In the smaller sizes, up to NEMA size 3, the vertical lift type has gained wide popularity. This type is illustrated in Fig. 116. An E magnet, or a solenoid, the armature of which moves in a vertical plane, carries the movable contact structure. Each pole consists of a double-break bridge type contact. Poles are separated from each other by insulating barriers. Both normally open and normally closed poles are shown. The contactor is bench assembled as a unit and all current-carrying parts are insulated from the magnet frame, which is structurally designed so that the contactor can be mounted either on a metal base or on an insulating base. The advantage of this style of contactor is its compactness, requiring less space than the former design with shaft and magnet on the side. There are few wearing parts, no pins and bearings, and long mechanical life is obtained.

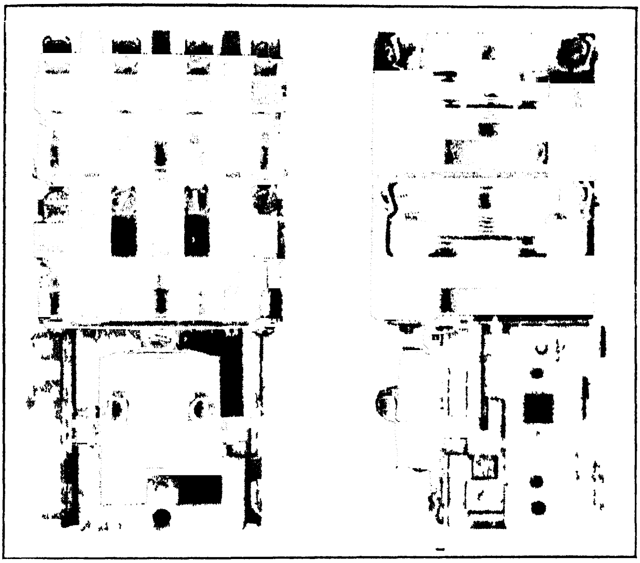


FIG. 116 NEMA size 00 vertical lift type a-c contactor with 8 poles, rated 10 amperes at 600 volts

No blowouts are provided. In a-c circuits current passes through zero twice every cycle, making it easier to interrupt a-c arcs than d-c arcs. When the contacts start to part, an arc forms across the contact tips. When the current passes through zero, the arc extinguishes. If the contact tips have parted a sufficient distance, it does not strike again. As long as the energy dissipated in the arc is moderate, a short gap between contacts suffices to extinguish the arc Contactors without blowouts have been built successfully for current ratings up to 100 amperes.

With large-size contactors, the amount of energy dissipated in the arc becomes too great to permit extinction without blowouts. As the vertical lift type contactor described above does not lend itself easily to the use of blowouts, larger contactors, in the 50- to 1000-ampere sizes, are usually built with a shaft and a magnet on the side. The magnet armature is connected to the rotating shaft, which in turn carries the movable contacts. Figure 117 illustrates this type of contactor, which is a self-contained unit suitable for individual or panel mounting. The blowouts are similar to the blowouts of d-c contactors, except that the iron cores of the blowout coils are laminated. The arc chutes, which confine the arc while it is being interrupted, are equipped in this case with labyrinth-like restrictions which cool the arc. When such contactors are used as secondary accelerating contactors for wound rotor motors, and if they close but do not open under current, blowouts and arc chutes are omitted.

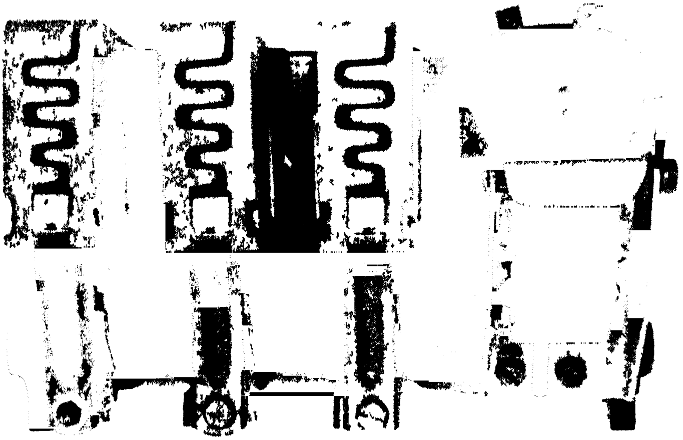


FIG. 117 NEMA size 4 triple-pole a-c contactor with clapper magnet

Electrical interlocks, operating simultaneously with the main power contacts, can be added to both types of contactors. Mechanical interlocks are used to prevent simultaneous closing of a pair of contactors, such as reversing contactors. Vertical lift contactors are mounted side by side, with a horizontal interlock between them. In shaft type contactors, the preferred arrangement is to mount contactors above each other with a vertical mechanical interlock between them.

With large contactors, it becomes difficult to build satisfactory a-c magnets. The shock of the heavy armature closing on the laminated magnet frame causes the edges of the laminations to spread and "mushroom." A solid magnet, excited by direct current, has inherently a longer mechanical life than a laminated a-c magnet. Thus large contactors are built with d-c magnets. This construction is used most often for contactors rated 600 amperes or higher, and it can be obtained optionally for smaller ratings. In addition to longer mechanical life, d-c magnets have the advantage that they present no noise problems.

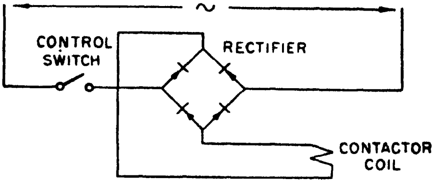
FIG. 118. NEMA size 5 triple-pole a-c contactor with d-c magnet.

Shown in Fig. 118 is a NEMA size 5 triple-pole contactor with d-c magnet. The arc chute of one pole is removed to show the construction details of the contacts, arcing horn, and blowout. The magnet consists of two solid soft steel cores and a soft steel frame and armature. The magnet is comparatively large and heavy, and the coils are designed for continuous duty at rated control voltage. The contactor shown is suitable for frequent operation. A saving can be made in size and cost of the magnet by using a smaller magnet with partial voltage coil. With the contactor open, full voltage is applied to the coil so that coil current is sufficiently high to close the contactor. When the magnet has nearly sealed, a normally closed interlock inserts resistance in series with the coil and reduces the coil current to such a value as to prevent overheating of the coil. The use of partial voltage coils and smaller magnets reduces the amount of power required from the control source to maintain magnetizing current. It is considered good practice as long as contactors are operated infrequently. On applications requiring frequent opening and closing of contactors, the frequently applied coil inrush current may cause coils to overheat.

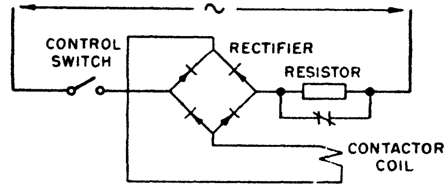
When a d-c supply is available in a plant, contactors may be operated directly from such a source.[2] If no direct current is available and a large number of contactors is installed, a small motor generator set may be the most economical means to obtain the necessary control power. When only a few contactors are to be operated with direct current, small metallic rectifiers are a more economical d-c source. Such rectifiers are discussed in greater detail in the next chapter. Although it is not essential to have a smooth d-c rectifier output voltage for successful contactor operation, half-wave rectifiers are to be avoided, as contactors are likely to chatter. Full-wave rectifiers are preferred.

Several methods of connecting rectifiers and contactor coils are indicated in Fig. 119. The simplest circuit *A* consists of a rectifier and a full-voltage coil. The rectifier must stand full voltage continuously and it must carry continuously a coil current sufficient to close the contactor. Although this circuit is simple and especially suited for frequent contactor operation, the rectifier is comparatively large and expensive. If contactors are operated infrequently, circuit *B* is preferred. The coil is designed for partial voltage, and resistance is inserted in series with the rectifier by an interlock when the contactor has nearly closed. The rectifier is subjected to full voltage and inrush current for only a very short time. After the contactor has closed, only partial voltage is applied and the current is reduced to a value necessary to hold the contactor closed. Thus a smaller and less expensive rectified can be used.

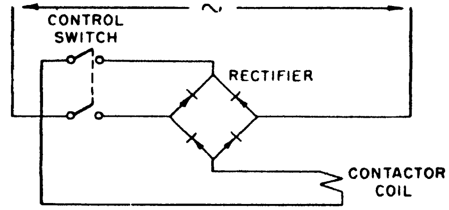
In sketches *A* and *B* a control switch is shown only on the a-c side of the rectifier. When the switch is opened, the coil circuit remains closed through the rectifier. On account of coil inductance, a discharge current will flow through rectifier and coil, making the contactor somewhat sluggish on drop-out. This sluggishness is rather objectionable on controllers for fast duty cycle drives requiring contactors to follow the opening and closing of pilot devices without delay. Fast drop-out can be obtained by circuit *C*. The control switch has two poles, one pole connected in the a-c side of the rectifier, and the second pole in series with the coil. If the control switch is opened, the coil circuit is interrupted, and no discharge path is available. Hence the contactor drops out fast.



A-CONNECTION FOR FULL POWER RECTIFIER



B-CONNECTION FOR MOST ECONOMICAL RECTIFIER



C-CONNECTION FOR FAST DROP-OUT

FIG. 119. Rectifier connections for a-c contactors with d-c magnets.

Contactors of very high current rating, say above 1000 amperes, are used only occasionally, since there is a tendency to use high-voltage motors in preference to low-voltage motors in sizes of several hundred horsepower or larger. Multi-pole contactors of such sizes would be rather bulky and expensive. Several single-pole d-c contactors are then used in combination, the blowouts of which are laminated. In order to insure that the several contactors comprising a multi-pole group operate together, the coils of all contactors of the group may be connected in series. If the coil of any one contactor is then open-circuited, the whole group will not close, thus avoiding the possibility of single-phasing a motor. The coils are energized either from an available d-c supply system or through rectifiers.

Contactors with d-c operating magnets can be built as latched-in contactors. A small permanent magnet, made of suitable material, such as alnico, is inserted in the magnet core. The permanent magnet has not sufficient strength to close the contactor, but it will hold the contactor closed once the magnet has been closed by electromagnetic action. The contactor magnet coil is split into two sections, the closing coil and the trip coil. When the closing coil is energized, the magnet closes. When the closing coil is de-energized, the contactor stays closed owing to the flux of the permanent magnet. Energizing the trip coil sets up a magnetomotive force which reduces the permanent magnet flux to the point where the contactor drops out.

Rating of Contactors

A-c contactors are widely used as line contactors in the primary or stator circuit of induction and synchronous motors. Safe contactor application demands that the contactor be able to disconnect the motor from the line under a stalled condition, and the contactor must be able to interrupt safely the current drawn by the motor at standstill. For this reason, standard ratings have been established by NEMA on the basis of both current and horsepower. The current rating is based on the ability of the contactor to carry its rated current for 8 hours without overheating of any of its parts. The horsepower rating determines the largest motor with which a given contactor can be used as a line contactor.

Table 6 lists standard NEMA ratings of contactors when applied as line contactors for single-speed full-voltage starters of squirrel

TABLE 6

STANDARD NEMA RATINGS OF A-C LOW-VOLTAGE CONTACTORS

		Horsepower Rating					
	Open 8-Hour Rating in Amperes	*110 Volts*		*220 Volts*		*440 and 550 V*	
Size		*Three Phase*	*Single Phase*	*Three Phase*	*Single Phase*	*Three Phase*	*Sing Pha*
00		¾	½	1	¾	1	
0	15	1½	1	2	1½	2	1
1	25	3	1½	5	3	7½	5
2	50	7½	3	15	7½	25	10
3	100	15	7½	30	15	50	25
4	150	25		50		100	
5	300			100		200	
6	600			200		400	

cage motors, full-voltage starters of multi-speed squirrel cage motors of the constant or variable torque type, reduced-voltage starters of squirrel cage motors, and secondary resistance starters of wound rotor motors. Accelerating contactors of single-step reduced-voltage starters for squirrel cage motors have the same rating as the line contactor, if the line contactor has an 8-hour rating of 150 amperes or less. If the line contactor is rated 300 amperes or more, the accelerating contactor may be one size smaller than the line contactor. If more than one starting step is used, accelerating contactors are selected so that their 8-hour rating for each step is not less than one sixth of the maximum current occurring on that step.

When contactors are used as line contactors for multi-speed squirrel cage motors of the constant horsepower type, the ratings of Table 6 do not apply. Instead, contactor ratings in accordance with Table 7 are used. Another exception to Table 6 is the application of line contactors for synchronous motor starters. Standard contactor ratings are given in Table 8.

TABLE 7

STANDARD NEMA CONTACTOR RATINGS FOR MULTI-SPEED CONSTANT HORSEPOWER SQUIRREL CAGE MOTORS

Size	*Open 8-Hour Rating in Amperes*	*Horsepower Rating*		
		110 Volts	*220 Volts*	*440–550 Volts*
00		¾	¾	
0	15	1	1½	2
1	25	1½	3	5
2	50	5	10	20
3	100	10	20	40
4	150	15	30	60
5	300		75	150

TABLE 8

STANDARD NEMA CONTACTOR RATINGS FOR SYNCHRONOUS MOTOR STARTERS

Open 8-Hour Rating in Amperes	*Horsepower Rating*			
	220 Volts		*440–550 Volts*	
	1.0 PF	*0.8 PF*	*1.0 PF*	*0.8 PF*
50	20	15	30	25
100	40	30	60	50
150	60	50	125	100
300	125	100	250	200
600	250	200	500	400
900	350	300	700	600
1350	500	400	1000	800

Ratings given in the above tables apply to contactors which are mounted in the open. When contactors are mounted on a large enclosed panel, the ambient temperature inside the enclosure hardly rises above the temperature outside so that the contactors are considered equivalent to being mounted in the open. However, if an individual contactor is enclosed in its own enclosing case, such as a full-voltage starter, the temperature inside the enclosure may rise above the temperature outside, and ventilation of the contactor is impaired. For such applications contactor ratings are reduced to 90 per cent of their standard 8-hour open ratings.

For intermittent duty, as encountered on cranes, special ratings have been established. The ampere ratings have been set at one third higher than the 8-hour rating, for contactors of an 8-hour rating of 100 amperes and higher. No intermittent ratings have been established for smaller contactors. In Table 9 the standard NEMA crane ratings are given. They are tabulated both in terms of amperes and, for line contactors, in terms of horsepower.

TABLE 9

STANDARD PRIMARY CONTACTOR RATINGS FOR A-C CRANE SERVICE

Open 8-Hour Rating in Amperes	*Crane Rating*		
	Amperes	*Horsepower at 220 Volts*	*Horsepower at 440–550 Volts*
50	50	15	25
100	133	40	75
150	200	60	125
300	400	150	300
600	800	300	600
900	1200	450	900
1350	1800	600	1200

Secondary accelerating contactors of wound rotor motor controllers are selected on the basis of their ampere rating. As secondary currents vary greatly for a given horsepower rating, depending on the speed and specific design of the motor, there is no relationship between secondary current and motor horsepower rating. On starters operated with push buttons, the secondary contactors close but do not open under current. Blowouts are usually omitted. Only the last accelerating contactor carries motor current continuously and has to be selected on the basis of its 8-hour rating. Intermediate contactors may be selected with a lower rating. Their continuous rating should be not less than one sixth of the maximum current occurring when each contactor closes.

On speed-regulating or duty cycle controllers, secondary contactors are opened and closed under the influence of a pilot device, such as a master switch. Blowout type contactors are then used, as any contactor may interrupt motor load current. All contactors are selected on the basis of secondary full-load current, except for controller steps on which such a large amount of resistance is inserted in the rotor circuit that the secondary current cannot possibly reach the rated full-load value. For such controller steps contactors are selected on the basis of actual maximum current which may be drawn on that step. For instance, if a contactor closes on a controller step with per unit resistance 2.0 in the rotor circuit, current drawn at standstill cannot exceed 0.5 full-load current, and the contactor need only have a rating of one half full-load current.

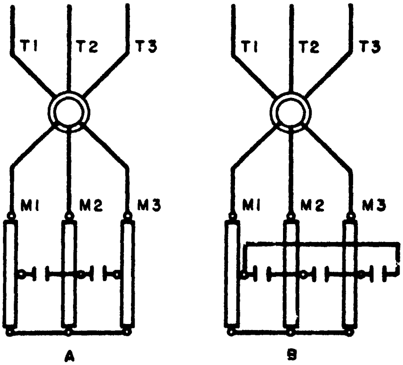


Fig. 120. Connections of secondary contactors for wound rotor motors. *A*. Double-pole contactor, open delta connected Contactor rating 100 per cent of normal. *B*. Triple-pole contactor, delta connected Contactor rating 150 per cent of normal.

Secondary contactors of wound rotor motor controllers can be connected in two ways, as indicated in Fig. 120. Double-pole contactors are open delta connected. See sketch *A*. Each contactor pole carries full rotor current, and contactor rating is equal to full-load rotor current. Triple-pole contactors are delta connected. See sketch *B*. Each contactor pole carries only a portion of the rotor current, which, with perfect distribution of current between poles, would be $1/\sqrt{3}$ of the rotor current. Because of slight variations in contact resistance, secondary resistance per phase, and lead resistance, perfect distribution of current between poles cannot be achieved in practice. It is assumed that the maximum current any contactor pole may carry is 1/1.5 of the rotor current. Delta-connected secondary contactors are applied on the basis of 1.5 times their normal current rating. As an example, a triple-pole 100-ampere contactor can be used as a secondary contactor for a motor having a rotor current of 150 amperes.

High-Voltage Contactors [3]

With motor line voltages above 600 volts, low-voltage contactors can no longer be used. Contactors are available which are especially

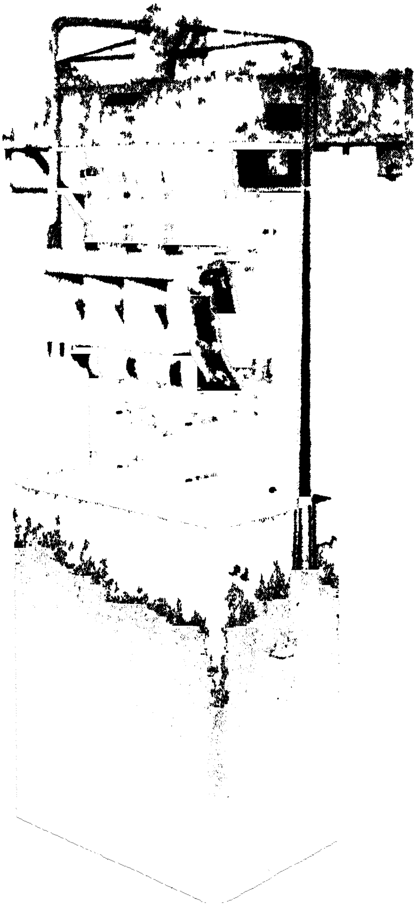


Fig. 121. Oil-immersed high-voltage a-c contactor rated 100 amperes, 2500 volts.

designed for operation on high-voltage circuits. Most commonly used high voltages for motor circuits in the United States are 2300 and 4600. Motor controllers for circuits up to 6000 volts are considered within the domain of industrial control. Very large motors for connection to higher voltage circuits are not often used, and generally, their applications do not require that they be started and stopped frequently. Circuit breakers and switchgear equipment control such motors, which are considered to be outside the scope of this book.

There are two categories of high-voltage contactors, the oil-immersed and the air break type. A typical three-pole oil-immersed contactor is shown in Fig. 121. It has an 8-hour rating of 100 amperes or 350 horsepower at 2300 volts. The contactor proper resembles a conventional low-voltage contactor, and the magnet is of the same construction. The contacts are assembled on a shaft, on which are molded grooved insulating spacers to increase the creepage distance between poles. The whole contactor assembly is immersed in a tank filled with oil. The oil serves to insulate current-carrying parts from each other and from ground. It also quenches arcs when the contactor opens under load. On oil-immersed contactors, blowouts are omitted since the arc is extinguished principally by the high-pressure gas formed as a bubble around the contacts when the heat of the arc decomposes some oil. Insulating barriers separate the poles and minimize the hazard of an arc-over between poles. A winch, operated by a hand crank, permits the oil tank to be lowered for inspection and maintenance.

The principal advantages of oil-immersed contactors can be summarized as follows:

1. Since all current-carrying parts are enclosed and confined in the oil tank, maximum protection to operating personnel is afforded.
2. The insulating value of oil permits distances between current-carrying parts to be kept low. As arcs are quenched by oil, arcing distances need not be much larger than on low-voltage contactors. Oil-immersed contactors can be built compact, requiring a minimum amount of space.
3. Oil protects the metal parts against corrosion.

These advantages are to some extent offset by the following disadvantages:

1. The presence of a body of oil constitutes a fire hazard. Care must be taken to provide good maintenance, as oil leaks constitute a definite danger.
2. Oil changes its properties in time, and sludge forms inside the oil tank. Regular cleaning of the contactor is necessary, and sludged oil must be replaced periodically by clean oil.

3. Contacts interrupting current under oil burn away more rapidly than contacts interrupting current in air. Oil-immersed contactors should not be used for motor controllers that operate frequently.

Air break high-voltage contactors avoid these disadvantages. As the name implies, the contacts interrupt arcs in air. A triple-pole contactor is shown in Fig. 122. Only one arc chute is assembled in place, and the right-hand pole piece and blowout coil shield are removed so that the details of contact construction can be seen. The magnet, either d-c or a-c operated, does not differ from those used on conventional low-voltage contactors. The shaft and tie rods, which support the contacts in the frame, are carefully insulated by baked-on layers of material with high dielectric strength, over which grooved insulating spacers are slipped, providing ample creepage distance between poles. Since only air insulates poles from each other, the spacing between current-carrying parts is considerably larger than on low-voltage or oil-immersed contactors. An air break contactor takes up considerably more space than an oil-immersed contactor of corresponding rating.

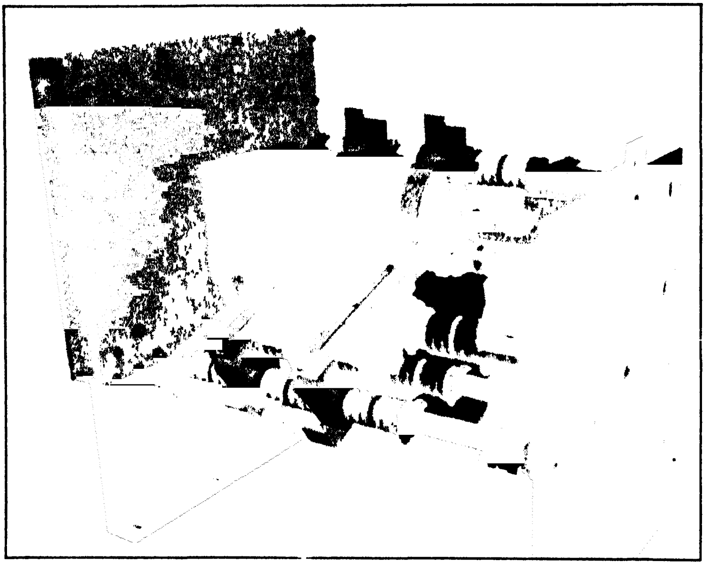


FIG. 122. High-voltage air break a-c contactor, rated 100 amperes, 2500 volts.

Blowouts interrupt the arcs when the contactor opens under current. Large arc chutes confine the arc, and baffle plates inside restrict the chute opening. Long arcing horns are provided, both on the stationary and the movable contacts, to control the movement

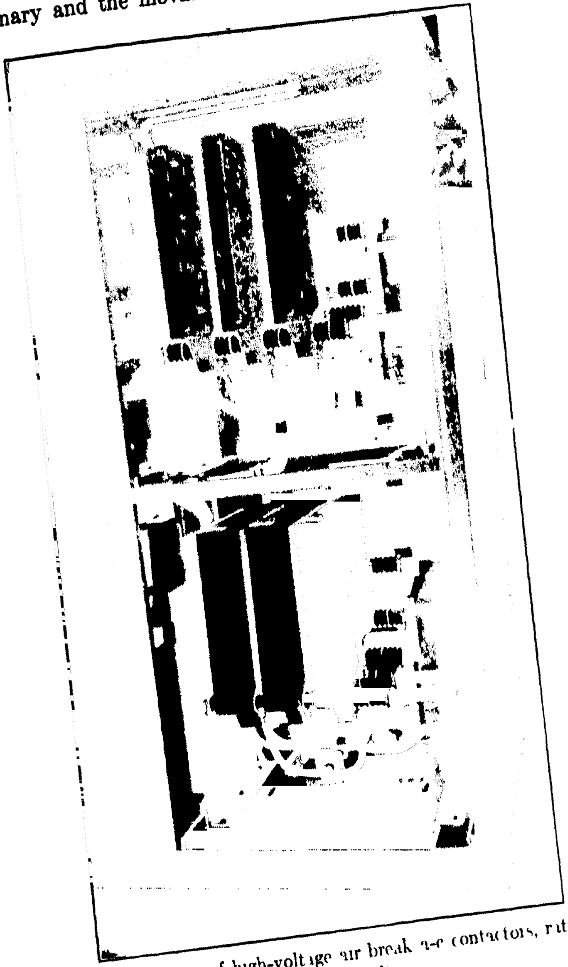


FIG. 123. Enclosed pair of high-voltage air break a-c contactors, rated 100 amperes, 2500 volts

of the arc and to carry it away from the contact tips to prevent excessive burning of the tips. High-voltage arcs are considerably longer and more difficult to extinguish than low-voltage arcs. Their movement must be restricted to avoid a flashover between poles, as the length of an arc may become several feet. Double blowout coils are used. One coil, consisting of a few turns, is connected to the stationary contact tip. When the tips part, a short arc is formed between stationary and movable tips, and a moderate blowout flux slowly increases the length of the arc and transfers it to the arcing horns. The second blowout coil, containing a large number of turns, is connected to the stationary arcing horn. As soon as the arc is transferred to the arcing horns, the full blowout flux elongates the arc rapidly and propels it along the surface of the arcing horns, causing it to extinguish quickly.

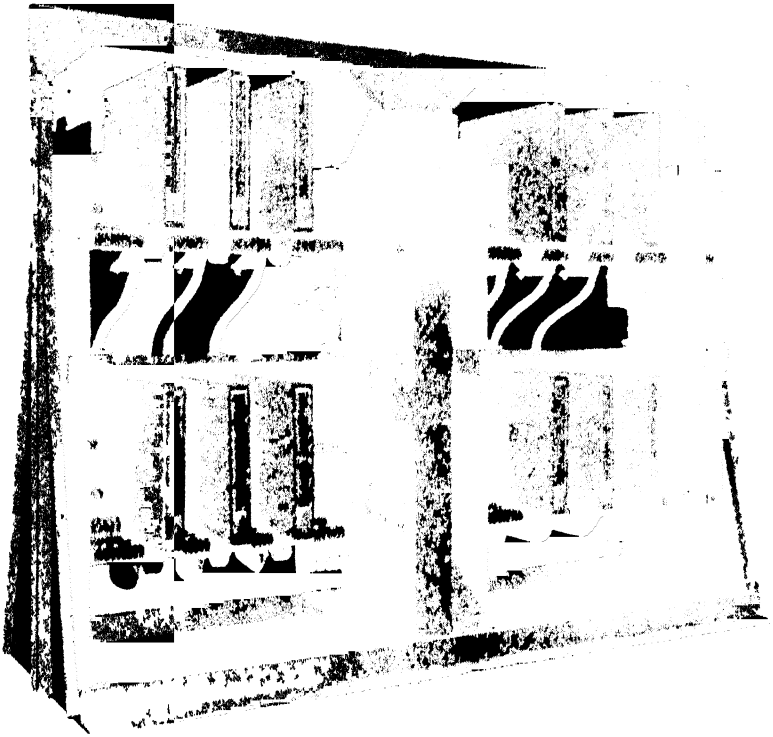


FIG. 121 Pair of high-voltage reversing air break contactors, rated 100 amperes, 6000 volts.

Air break high-voltage contactors require considerable space. When open contactors are installed, care must be taken to prevent personnel from coming in contact with any current-carrying parts. Safety can be increased greatly by enclosing contactors, as illustrated in Fig. 123. The absence of oil reduces maintenance, increases tip life, and makes air break contactors particularly suited for applications requiring frequent starting and stopping of motors, such as mine hoists, cableways, aerial tramways, and the like.

Contactors for 4600-volt circuits are built like 2300-volt contactors, except that the spacing between poles and to ground is somewhat increased. For 6000-volt motors, two contactors are arranged so that there are two breaks in series in each primary phase. Shown in Fig. 124 is a pair of reversing contactors for a 6000-volt mine hoist motor, assembled on a common framework. The two left-hand contactors close together, to connect the motor to the line in the forward direction. The poles of the upper contactor are connected in series with the poles of the lower contactor. Likewise, the right-hand pair of contactors closes simultaneously to connect the motor to the line in the reverse direction.

Control Relays

Control relays are used for many purposes. Some types perform specific functions, others simply close or open their contacts when their coils are energized, in order to provide sequencing or interlocking circuits. To permit energizing control relays by the light and sometimes delicate contacts of pilot devices, it is essential to keep both magnetizing and inrush current of the relay magnet as low as possible. Solenoids are preferred as operating magnets.

A typical solenoid-operated control relay is illustrated by Fig. 125. The cover is removed to show details of magnet and contacts. It can be supplied with any desired number of circuits, up to six, and contacts may be either normally open or normally closed. Small contactors, as shown in Fig. 116, are also often used as control relays.

Control impulses may be initiated by sensitive instruments, the contacts of which are too delicate to interrupt the coil current of a magnet but are able to close and carry the magnet coil current. For this purpose relays are used of a type shown in Fig. 126. The relay coil is connected in series with a resistor. When the instrument contact marked "close" is closed, the relay is energized, and it seals itself in through its own holding interlock. When the "close" contact is opened, the relay stays energized. When the "trip" contact is closed, it short-circuits the relay coil and the relay drops out. The instrument contacts close, but never open, under current. This type of relay is used most frequently in connection with thermostats or temperature control instruments. For this reason, relays which are de-energized by closing, rather than opening, a pilot circuit are generally known as *thermostatic relays.*

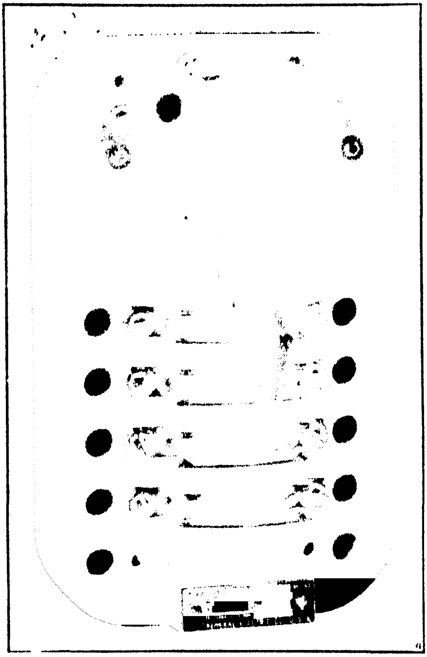


Fig. 125. Four-pole control relay, rated 15 amperes, 600 volts, with cover removed.

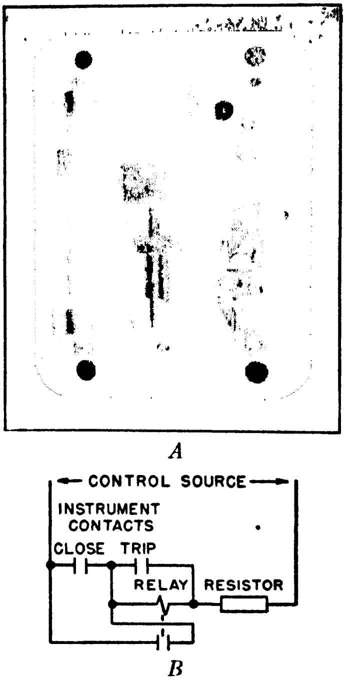


Fig. 126. Thermostatic control relay. *A*. Front view of relay. *B*. Basic relay connections.

Timing Relays

In Chapter 4 simple and rugged d-c magnetic time delay relays have been described, the operation of which is based on the gradual decay of magnetic flux. With the development of small and reliable metallic rectifiers, d-c timing relays have found wide application on a-c controllers. As the timing principle of such relays necessitates the presence of direct current, relay coils are connected to a-c control sources through rectifiers. Relays may either be equipped with individual rectifiers, or a group of several relays may be connected to a common rectifier. Flux decay timing relays have an inherently long life because of the absence of mechanically wearing parts, such as gear trains. D-c timing relays are especially desirable for use on intermittent-duty controllers, where the relays are subject to frequent operation.

Long time delays, of the order of minutes or even hours, are obtained by means of motor-driven timing relays. A typical timing relay is shown in Fig. 127 with cover removed so that the timing mechanism can be seen. When the relay is energized, a solenoid-operated clutch engages a gear train, which is driven by a self-starting synchronous motor of a type used in electric clocks. The motor turns a cam, until the relay contacts are opened or closed.

FIG. 127. Motor-driven a-c time delay relay.

The motor is then disconnected and stopped, but the clutch solenoid holds in the contacts. When the solenoid is de-energized, the relay contacts reset. Timing is adjusted by a knurled disk which shifts the position of the contact-actuating cam. It, in turn, determines the amount of cam travel required to open or close the relay contacts.

Current Limit Relay

Many applications require a relay which responds to the current taken by the motor to be controlled. Such a relay is shown in Fig. 128. Its magnetic circuit contains two coils and two plungers. The front coil is a shunt coil, which is connected across the control source. The back coil is a current coil, which is connected in the motor primary circuit, either directly or through a current transformer. The plunger in the current coil actuates the relay contact. As long as the plunger is raised, the relay contact is open. When the current coil plunger drops, the relay contact closes.

This relay is used primarily as an accelerating or plugging relay, and the principles of its application to control circuits are explained in Chapter 12. As long as the shunt coil is de-energized, the weight of its plunger overcomes the weight of the current coil plunger through the lever at the bottom of the relay. The current coil plunger is raised, and the relay contact is locked open. When the shunt coil is energized, its plunger is raised, and the contact is then under control of the current coil. As long as the motor current exceeds the setting of the relay, the current coil plunger stays in the raised position. When the motor current drops below the relay setting, the current coil plunger drops, and the relay contact closes. A holding coil holds the relay contact firmly closed should motor current fluctuations accompany the closing of the relay.

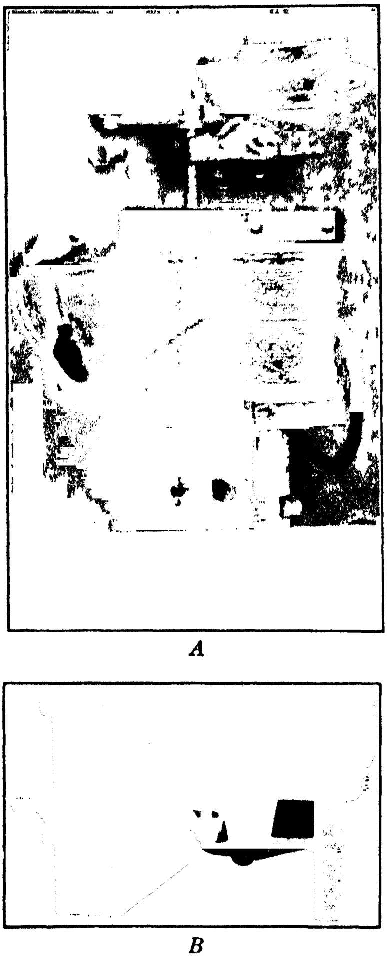


Fig. 128. A-c current limit relay. *A*. Front view of relay. *B*. Detail of lever arrangement.

Phase Reversal and Phase Failure Relays

The direction of rotation of a-c motors is determined by the phase rotation of the a-c line voltage. Accidental reversal of line phases would result in inadvertent motor reversing. Relays are available which stop and prevent starting of motors in case of line phase reversal. Such relays, while not considered necessary for all motor applications, are required in cases where accidental motor reversal involves a serious hazard to life.

Two types of phase reversal relays are available based on either the current or the voltage principle. Figure 129 illustrates a relay of the current type. Four magnets, the coils of which are excited by the current of two stator phases of the motor, set up a rotating flux which intersects a solid disk, pivoted in the center. Eddy currents are induced in the disk, and a torque is developed which tends to rotate the

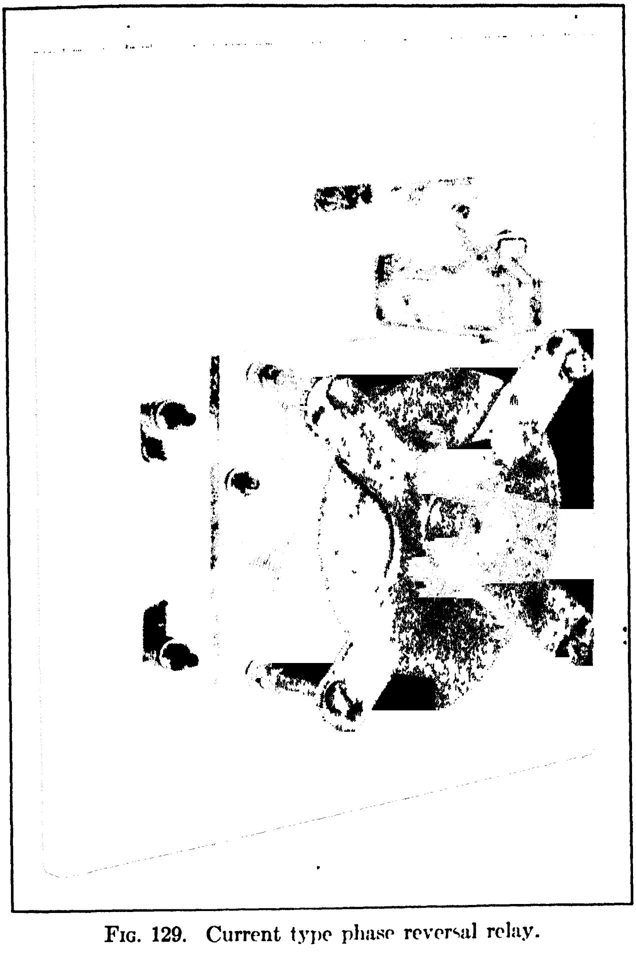


FIG. 129. Current type phase reversal relay.

disk. As long as line phase rotation is correct, the torque of the disk is in the direction to press the disk against a stop, and the relay contacts are closed. When line phase rotation reverses, the flux set up by the magnets reverses, and the torque of the disk reverses. The disk is free to rotate in the opposite direction, and it trips the contact open. When the relay contact is connected in the coil circuit of the motor line contactor, the motor is disconnected from the line. The relay shown is reset manually.

A voltage type phase reversal and phase failure relay is shown in Fig. 130. The magnet is built like the magnet of a watthour meter, and its three coils are connected to the three lines of the power system. A metallic vane is pivoted so that it swings in the air gap of the magnet. When all three phases of the power system are alive, and if phase rotation is correct, the torque on the vane is in a direction to close the relay contact. If phase rotation reverses, the torque on the vane reverses, and the relay contact opens. If one or several phases open, the flux distribution in the air gap of the magnet changes, and no torque acts on the vane. The relay contact then opens under the influence of the weight of the vane.

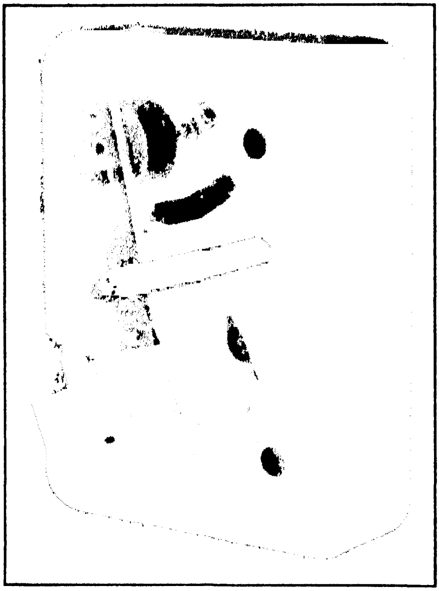
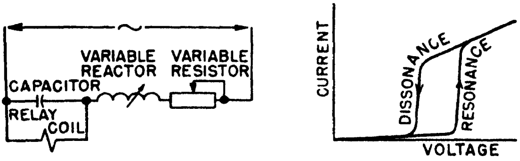


Fig. 130. Voltage type phase reversal and phase failure relay.

The voltage type relay opens its contact instantly upon phase reversal. Its operation upon loss of one phase depends on whether or not the motor happens to be running when one phase of the line is interrupted. If the motor is standing still, the relay opens its contact and prevents connecting the motor to the line single phase. If the motor is running when one phase of the line fails, a voltage is induced in the third phase of the motor primary winding by the remaining two phases of the motor winding. The induced voltage appearing at the third motor terminal holds in the relay. This is desirable on controllers for intermittent drives, as the relay permits a motor to finish a trip before it opens and prevents restarting of the motor, after it has stopped.

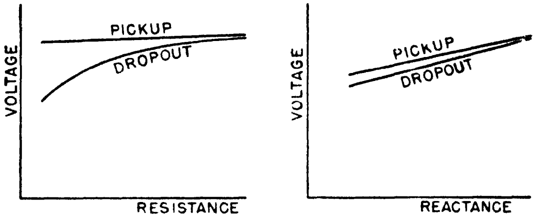
Resonant Relays[4]

The use of a non-linear circuit, composed of capacity, inductance, and resistance, permits relays to respond very accurately to changes in voltage. The source of non-linearity is the behavior of the reactor, which contains an iron core that saturates. When a varying voltage is applied to the reactor, the current through the reactor does not change proportional to the voltage, and the inductance is reduced with increasing saturation. Therefore, the reactance of the reactor is determined not only by the frequency but also by the voltage applied to the reactor. When the reactor is then used in a resonant circuit, resonance at a given frequency occurs only at a certain voltage. Consider the series resonant circuit of sketch *A* in Fig. 131. If an alternating voltage is applied to the circuit, and the voltage is gradually raised, the current at first is low and increases slightly with increasing voltage. When a certain voltage is reached, the magnitude of which depends upon the circuit constants, a resonant condition exists. The



A-CONNECTIONS OF RESONANT VOLTAGE RELAY

B-VOLTS—AMPERE CHARACTERISTIC OF CIRCUIT A



C-RELAY CHARACTERISTIC FOR VARYING RESISTANCE

D RELAY CHARACTERISTIC FOR VARYING REACTANCE

FIG. 131. Connections and characteristics of resonant voltage relay.

circuit becomes unstable, and the current jumps suddenly to a much higher value. Further increase in voltage results in a further gradual increase in current. If the voltage is then decreased again, the current gradually decreases until a voltage is reached below the point of resonance. At this voltage the circuit becomes dissonant again, and the current suddenly decreases to a low value. This circuit behavior is illustrated by sketch *B*.

Variations in capacity and inductance determine the voltage at which resonance occurs. For practical applications, it is difficult to build capacitors which can be varied easily. However, the inductance can be varied without appreciable design difficulties by building a reactor with an adjustable air gap. The amount of resistance determines the voltage at which dissonance occurs.

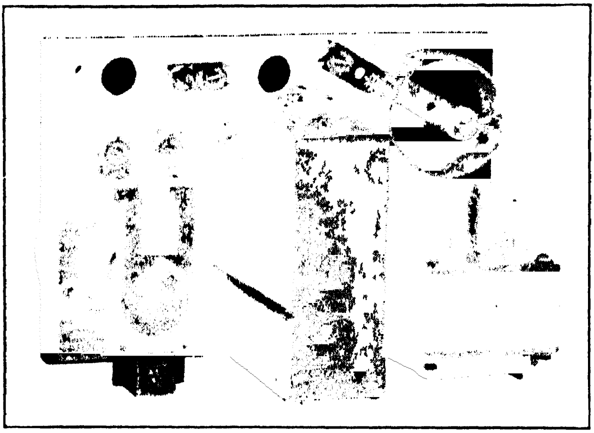


FIG. 132. Resonant voltage relay.

Non-linear behavior of the circuit can be used for actuating a relay. When the coil of a relay is connected across a portion of the resonant circuit, it measures the drop across that circuit element, which is a measure of current. The most satisfactory arrangement is to connect the relay coil across the capacitor, as indicated in sketch *A*. The voltage at which the relay picks up is governed primarily by capacity and inductance, whereas the voltage at which the relay drops out is determined by the adjustment of the resistor. As can be seen from sketch *C*, the differential between pick-up and drop-out voltage decreases as the resistance is increased. It is possible to build relays on which the differential between pick-up and drop-out voltage can be adjusted between 0.25 and 30 per cent of the pick-up voltage. Changing the reactance by adjusting the reactor air gap permits varying of both pick-up and drop-out voltage over a range of approximately 30 per cent.

As relay performance depends on a resonant circuit condition, it is affected by changes in frequency of the control circuit. As long as frequency changes remain within a small percentage, the voltage response of the relay varies approximately in proportion to frequency variations.

Figure 132 is the front view of a voltage responsive resonant relay. The component parts are assembled on a base, and the cover is omitted to show the details of construction. On the left side is the magnetic relay. In the center is the capacitor. On the right is the rheostat with screwdriver adjustment of drop-out. Below it is the reactor with screwdriver adjustment of pick-up, by adjustment of its air gap.

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CHAPTER 6

ACCESSORIES

Complete magnetic control equipments often contain not only contactors and relays necessary to obtain specific operation of the machines to be controlled but also switches or circuit breakers used to isolate equipments from incoming power circuits. Circuit breakers also afford overcurrent protection. Transformers obtain control voltages of desired magnitude, and rectifiers provide for auxiliary direct current from a-c systems. Voltage regulators maintain control voltage under varying load conditions. Such devices are classified as accessories. They do not respond to control signals and impulses, but they set up and prepare the circuits on which control devices perform their functions.

Many additional accessory devices are at times found on control panels such as instruments, meters, instrument transformers, clocks, indicators, and the like. Their use, however, is ordinarily not essential to the desired performance. For this reason, they are not discussed in this book.

Knife Switches

Knife switches are frequently used to isolate power and control circuits. Enclosed safety switches are sometimes provided between incoming power lines and the line contactors of magnetic controllers. Safety switches serve a dual purpose. They isolate the controller so that it can be serviced without danger of contact with live parts. They must also be able to interrupt the power circuit under full-load condition by hand, in case of an emergency. However, switches are not intended to be opened under short-circuit conditions. Safety switches are rated in terms of horsepower, denoting the largest motor to which a switch of a given voltage and ampere rating can be applied.

Open knife switches, as used on magnetic control panels, are considered disconnecting means, not to be used for power switching. They are rated in terms of amperes and are expected to carry current, but not to interrupt motor loads. Their chief purpose is to isolate a controller from the line or to isolate certain motor circuits, in the case of multi-motor controllers. Lockouts, for locking a knife switch open by means of a padlock, give assurance to an electrician that no one but himself can energize a circuit on which he may be working.

No intermittent current ratings have been established for knife switches. On intermittent rated controllers, knife switches having an ampere rating equal to the 8-hour rating of the power contactors of the controller are used.

Knife switches are widely used as control switches to isolate control circuits. Separate power and control switches permit closing of the control circuit only and testing of the control devices, without energizing the motor. When control switches are used on d-c controllers the amount of inductance in the control circuit should be considered. When the control circuit inductance is high, either because of a large number of heavy contactor coils or when d-c machine fields are connected to the control circuit, special field discharge switches are used. Such switches are equipped with an auxiliary blade which connects a discharge resistance in the circuit when the switch opens, thus avoiding excessive arcing on the switch contacts and high voltage surges across the control circuits.

Whether or not power and control disconnect switches are included as part of a control panel depends largely on the preference of the user. It is customary for manufacturers to offer standard general-purpose controllers without either line or control switches, and it is assumed that the purchaser provides disconnecting means apart from the controller. On special control panels, disconnect switches are included in the majority of cases, especially if a multiplicity of motors is controlled by a group controller. Convenience to the operator and saving of installation expense favor disconnect switches on control panels rather than separately mounted switches.

Circuit Breakers

Functionally, circuit breakers serve both as disconnecting means and as protective devices. As compared with switches, they possess much higher interrupting ability. They are either manually operated or they are remotely operated through solenoids or motor mechanisms. Most circuit breakers are equipped with automatic overcurrent trips which open the breakers if the current through the breaker exceeds the trip setting. Circuit breakers are designed to interrupt overloads and fault current, and their primary purpose as part of controllers is to protect the control equipment against damage due to short circuits. The selection of circuit breakers for any installation must be based not only on their continuous current rating but also on their interrupting ability, which must be at least as great as the largest fault current the system can produce at the point of breaker installation. Selection of circuit breakers is governed by analysis of the power system rather than motor performance. As an optional item, certain types of circuit breakers can be provided with undervoltage trips which cause the breakers to open if either line or control voltage fails. For a more detailed discussion of the selection of circuit breakers for purposes of protection, refer to Chapter 14.

The functions of circuit breakers and contactors in a controller should not be confused. Contactors are designed for frequent operation and for interruption of motor loads and operating overloads; circuit breakers are ordinarily designed for less frequent operation and for interruption of high fault currents. Breakers stay closed for long periods of time, but they must be relied upon to trip and clear the system promptly when an unusual overload or fault condition occurs. Except for drives that are started infrequently, contactors, rather than circuit breakers, should be used for starting and stopping.

Oil circuit breakers are among the oldest devices used to interrupt current. They are used today principally in installations over 600 volts, although they have also been used on lower voltage circuits. The arc formed during circuit interruption is quenched by the oil inside the tank which also serves as insulation for live parts inside the tank. Figure 133 shows the front view and back view of a manually operated oil circuit breaker, rated 2500 volts, with an interrupting rating of 15,000 kva. This particular breaker is used as main line breaker of a 440-volt installation.

Advances made in the design of air circuit breakers have greatly curtailed the use of oil circuit breakers on low-voltage controllers. As the name implies, the arc of an air circuit breaker is interrupted in air. From the point of view of the control designer, air circuit breakers have the advantage that they are easier to mount on a control panel. Contacts can be inspected without having to lower an oil tank. The possibility of oil leaks and the resultant fire hazard are eliminated. Air circuit breakers can be obtained for manual or remote operation, with instantaneous and/or time delay overcurrent trips and with instantaneous or time delay undervoltage trips.

Shown in Fig. 134 is a typical manually operated air circuit breaker, installed in an enclosed control panel. Arc quenchers are behind a barrier which confines the arcs and prevents their striking structural panel parts. The breaker is rated 600 volts, 600 amperes, with an interrupting rating of 25,000 amperes. It is equipped with dual instantaneous and time delay overcurrent trips.

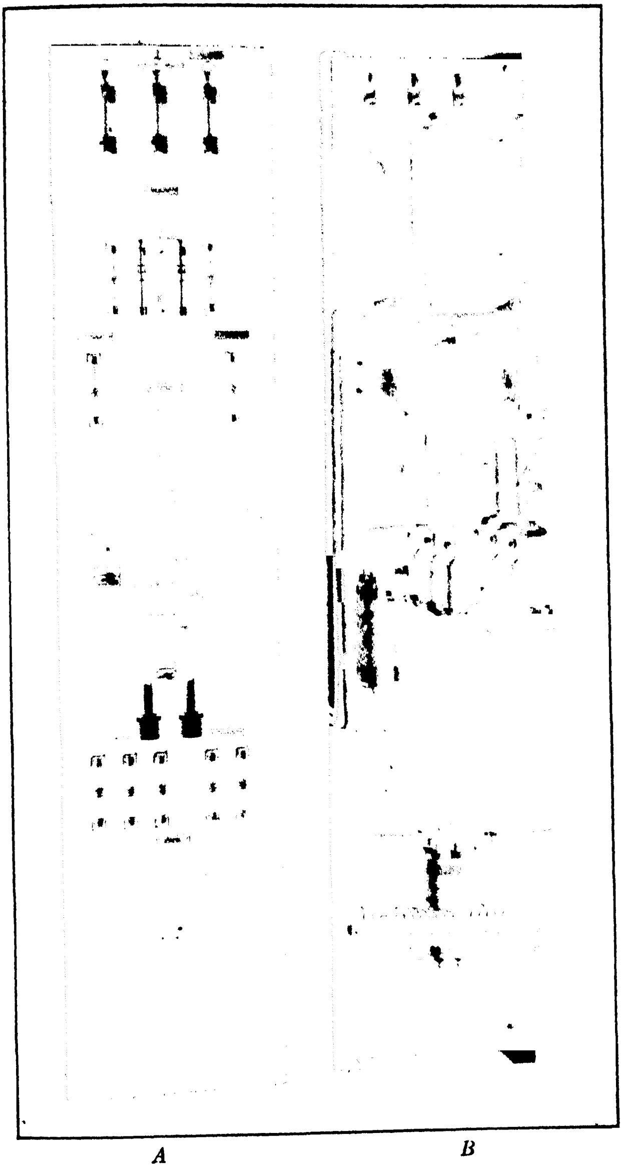


Fig. 133. Manually operated oil circuit breaker, rated 2500 volts, 15,000-kva interrupting rating, mounted on control panel. *A*. Front view. *B*. Back view.

Central station practice often favors the use of a battery for closing and tripping of breakers. The cost of the battery and the necessary charging equipment is in most cases not warranted for industrial control installations Operating mechanisms, either of the solenoid or motor type, are operated from a low-voltage control source. Overcurrent and undervoltage trips are generally direct acting.

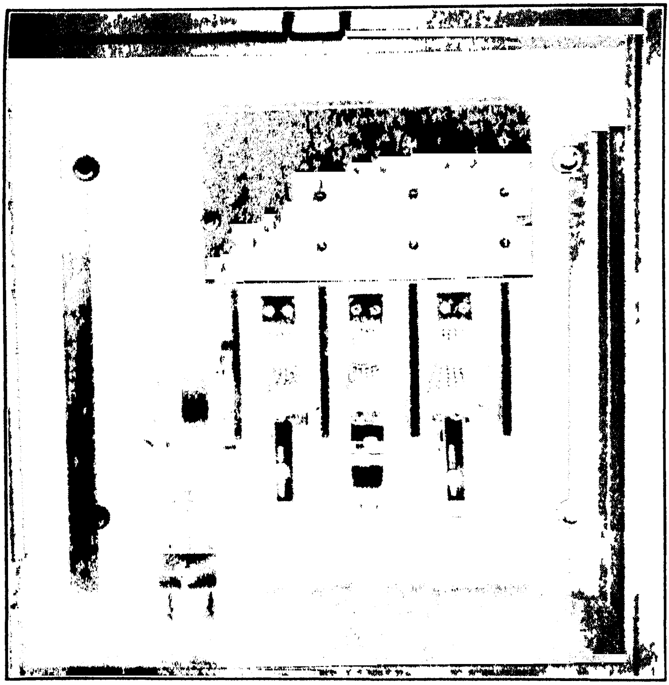
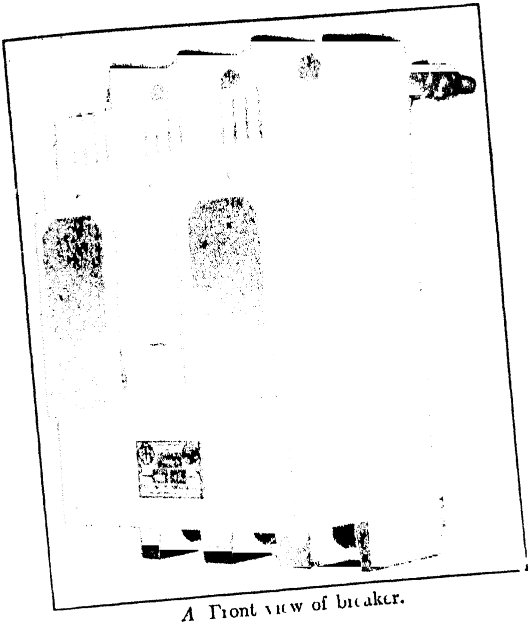


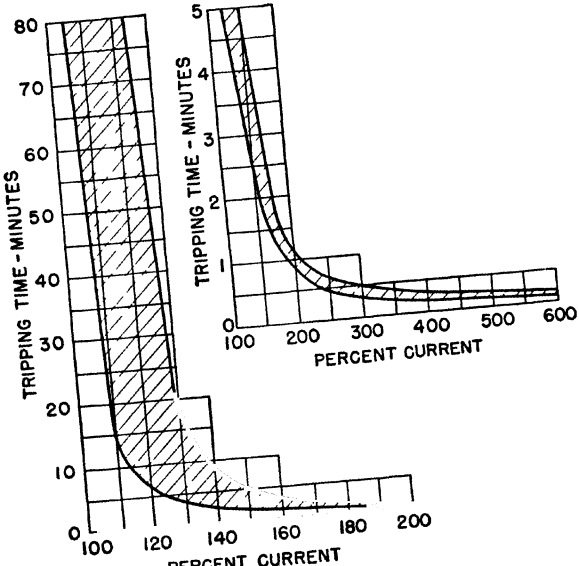
FIG. 134. Manually operated air circuit breaker, rated 600 amperes, 600 volts, 25 000-ampere interrupting rating

The advent of small panelboard type circuit breakers for lighting distribution purposes has brought about the development of small, compact, manually operated air circuit breakers, which have found wide application in industrial installations[1] Such breakers are available as double- or triple-pole forms, in standard frame sizes of 50, 100, 225, and 600 amperes Each frame size is built in several current ratings, determined by the overcurrent trips. The interrupting ratings are 5000 to 15,000 amperes.

Figure 135 shows a typical breaker, rated 15 amperes, 600 volts alternating current or 250 volts direct current, 100 ampere frame,



A Front view of breaker.



B Tripping curve

Fig. 135 Small manually operated air circuit breaker, 100-ampere frame, 10,000-ampere interrupting rating (Courtesy I-T-E Circuit Breaker Co.)

10,000 ampere interrupting rating. Figure 135*A* is a front view of the breaker. Figure 135*B* is a tripping curve with tripping time plotted versus current. Individual breakers of a line vary somewhat in their tripping characteristics. Two curves are therefore shown, designating the maximum and minimum tripping time for any value of current. The actual tripping characteristic of an individual circuit breaker falls between the two curves.

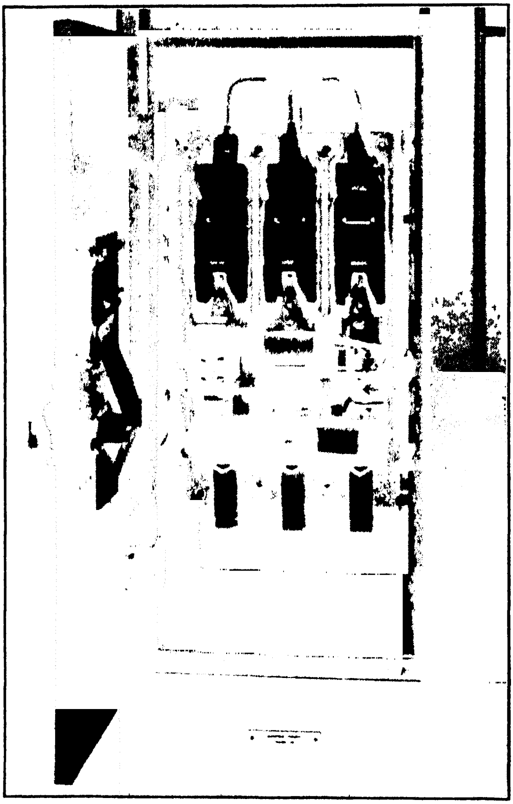


FIG. 136. Small air circuit breaker, 225-ampere frame, with cover removed, mounted in enclosed compartment.

Such air circuit breakers are widely used in place of fused disconnect switches, both for motor and control circuits. They afford short-circuit protection. Their tripping characteristic is of the inverse time type, a thermal trip for overloads and a magnetic trip for high short-circuit currents being used generally. As compared with fuses, they trip more slowly on short circuits but they trip faster on moderate overloads. They should be considered primarily as branch circuit breakers. Their place as protective devices in control systems is discussed in greater detail in Chapter 14.

Compactness makes these breakers especially suited for panel mounting. Figure 136 shows a 225-ampere frame circuit breaker installed in a panel compartment. The cover of the breaker is removed so that details of internal construction may be seen. The compartment door is equipped with a breaker-operating handle, permitting closing and tripping of the breaker without opening the door.

Control Transformers

Control transformers are used to step the system voltage down to a value suitable for the control circuits of a controller. On high-voltage systems above 600 volts it is always necessary to step the control voltage down from the supply system voltage, as it would be impossible to design pilot devices, contactor coils and the like, for operation on high voltage. Even on low-voltage circuits, it is desirable at times to step the control voltage down to a lower value

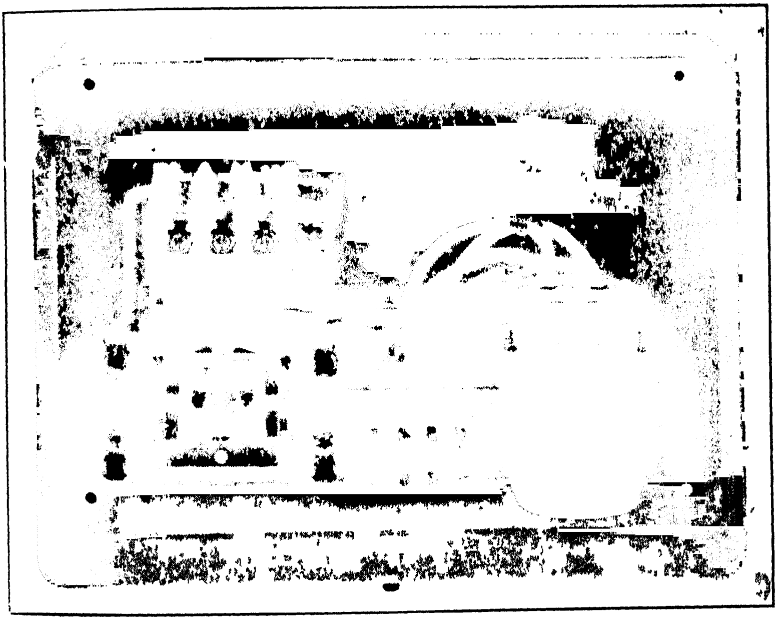


FIG. 137. Control transformer, rated 0 050 kva, mounted alongside contactor in enclosing case.

than the power system voltage. Delicate instruments, used as pilot devices, may not be able to operate on voltages above 110. In damp locations it may be too dangerous to have operating personnel come in contact with manually operated pilot switches carrying control circuits of higher voltage than 110. Pilot lamps are generally available only for 110 volts or less, to mention a few reasons for using step-down transformers.

Control transformers range between 0.050 kva and 5 kva capacity. On high-voltage controllers up to 4600 volts, and on low-voltage controllers, dry type transformers are most generally used because of their simplicity, ease of mounting, and low cost. In Fig. 137 a small control transformer, rated 0.050 kva, is mounted in a small enclosing case with the contactor, the coil voltage of which it supplies. In Fig. 133 a 3-kva control transformer can be seen mounted in the back of the panel.

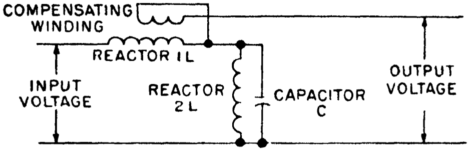
The selection of control transformer size is governed by the following considerations. The rated current of the transformer must not be smaller than the sum of the magnetizing currents of the largest number of contactors and relays which may be energized at one time. The highest current peak, which may occur because of the inrush current of one contactor, added to the magnetizing current of all other contactors, should not exceed three times the rated transformer current. Otherwise the regulation of the transformer would reduce the control voltage to a value too low to permit successful contactor operation.

Voltage Stabilizers

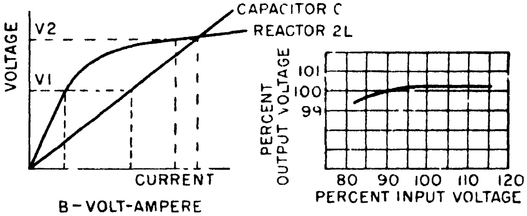
Control systems which provide control as well as maintenance of operating quantities, such as speed or voltage, require the presence of a constant-voltage source as a reference. Typical examples are amplidyne controllers for speed regulation, voltage regulation, current limit control, and the like. In many plants, a constant-voltage d-c source is not available and an a-c control source is used as a reference to save the expense of installing a motor generator set. To make the control system independent of fluctuations in the voltage of the power supply, voltage stabilizers are used which, when connected to a fluctuating input voltage, produce an output voltage that stays constant within narrow limits. Voltage stabilizers are sometimes combined with step-down transformers and marketed as constant-voltage transformers.

Voltage stabilizers make use of non-linear circuits to compensate for variations in input voltage. In Fig. 138 sketch *A* is the schematic diagram of one form of voltage stabilizer. It consists essentially of a reactor 1*L*, which is connected in series with a network consisting of saturable reactor 2*L* and capacitor *C* in parallel. A compensating winding, which compensates for voltage drop through reactor 1*L* because of load current, is wound on a common core with reactor 1*L*.

In sketch *B* is given the volt-ampere characteristic of the network consisting of 2*L* and *C*. When the impressed voltage is low, current through *C* is much larger than current through 2*L*. The capacitive current causes a drop through reactor 1*L* which adds to the input voltage. If the impressed voltage is high, the difference between current through 2*L* and *C* becomes smaller, and the drop through 1*L* deducts from the input voltage. By proper proportioning of 1*L*, 2*L*, and *C*, it is possible to keep the output voltage within narrow limits, even though the input voltage may vary considerably. Sketch *C* is a plot of output voltage versus input voltage at rated load and unity power factor, and the output voltage variation is well within 1 per cent over a considerable range of input voltage. In reference circuits of closed cycle control systems, load and power factor change very little, and a voltage stabilizer is suitable for providing a reliable reference voltage source.



A - ELEMENTARY CONNECTIONS



B - VOLT-AMPERE CHARACTERISTIC

C - VOLTAGE CHARACTERISTIC AT RATED LOAD, UNITY POWER FACTOR

Fig. 138. Voltage stabilizer.

Rectifiers

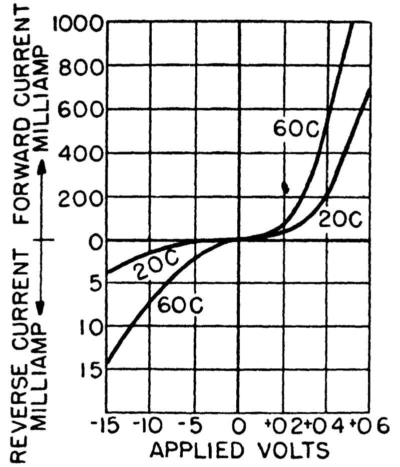
Rectifiers are devices used to convert alternating voltage and current into unidirectional voltage and current. As part of control equipments, rectifiers are used principally for two purposes. Most frequently, rectifiers are used to obtain a small amount of d-c power from an a-c system for the operation of contactors, circuit breakers, relays, or for the field excitation of small rotating machines. Occasionally, the valve action of rectifiers is made use of to permit passage of current in only one direction and to block current flow in the opposite direction. As an example, it may be desired to have a relay discriminate the change in polarity of a d-c machine.

Metallic rectifiers are used almost exclusively for control work. Their advantages are simplicity, the absence of auxiliary equipment, moderate cost, and instant availability. Accurate control of d-c output voltage is generally not required. Likewise, the ripple present in the rectified d-c voltage wave is usually of no importance.

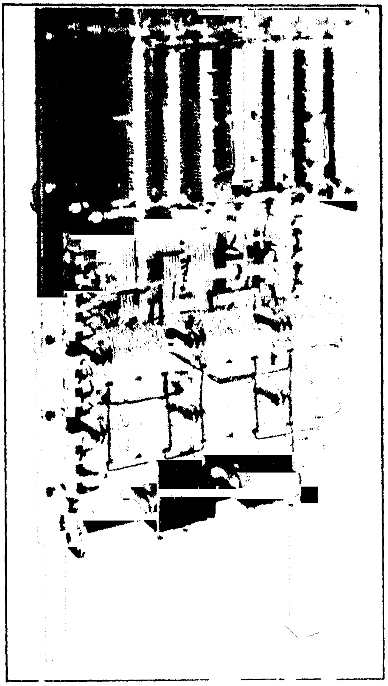
Two types of metallic rectifiers are most commonly used, copper oxide and selenium rectifiers. Both types function on the principle that the dividing layer between certain dissimilar materials offers a high resistance to current flow in one direction but a low resistance to current flow in the opposite direction. Their internal resistance changes somewhat with time, when rectifiers are aged. Some aging takes place whether or not rectifiers carry current. After approximately six months of use, copper oxide rectifiers become stable. Selenium rectifiers age continually. With increasing temperature, the resistance of rectifiers to reverse current flow decreases, and the maximum temperature at which they can operate is thus definitely limited. Copper oxide rectifiers and selenium rectifiers may be operated at temperatures up to 75 C, but they must be derated for use above 50 C. When installing rectifiers, care must be taken to mount them so as to keep the ambient temperature as low as possible. When resistors and rectifiers are mounted on the same panel, resistors should always be located above the rectifiers.

The active cell of a copper oxide rectifier [2] is a copper disk, on one side of which a film of cuprous oxide is formed. When voltage is applied to such a cell current flows readily from oxide to copper, but flow of current from copper to oxide is blocked. In Fig. 139, sketch *A*, the current-voltage characteristic of a single rectifier cell is plotted. Connecting several cells in series by stacking them on a bolt and clamping them tightly together forms a "stack," the rated terminal voltage of which depends on the number of cells in series. The current rating depends on the cell diameter and the number of cells connected in parallel. Cooling fins are often attached to the cells in order to increase the radiating surface. In Fig. 139*B* a group of rectifiers is shown mounted in the back of a control panel. The rectifiers are located below a bank of resistors so that hot air rising from the resistors does not raise the ambient temperature of the rectifiers.

A selenium rectifier cell consists of a metal plate, called the carrier plate, on which a very thin layer of selenium is deposited. By suitable heat treatment, a definite crystalline structure of the selenium is obtained. A layer of metal with low melting point is sprayed over the selenium, forming the counter electrode. By a subsequent electrochemical process a blocking layer is formed between the selenium film and the counter electrode. Current flows freely from the selenium to the counter electrode, whereas current flow in the opposite direction is practically blocked.



A



B

Fig. 139. Copper oxide rectifiers. *A*. Current versus voltage characteristic of a rectifier cell. *B*. Group of rectifier stacks mounted in back of control panel.

The voltage-current characteristic of a selenium rectifier cell[3,4,5] is similar to that of a copper oxide rectifier, as plotted in Fig. 140*A*. Individual cells are assembled in stacks, the voltage rating of which depends on the number of cells in series. Figure 140*B* shows selenium rectifier stacks of various sizes mounted on a panel.

By connecting sufficient cells in series, it is possible to build metallic rectifiers for direct connection to control circuits up to 600 volts.

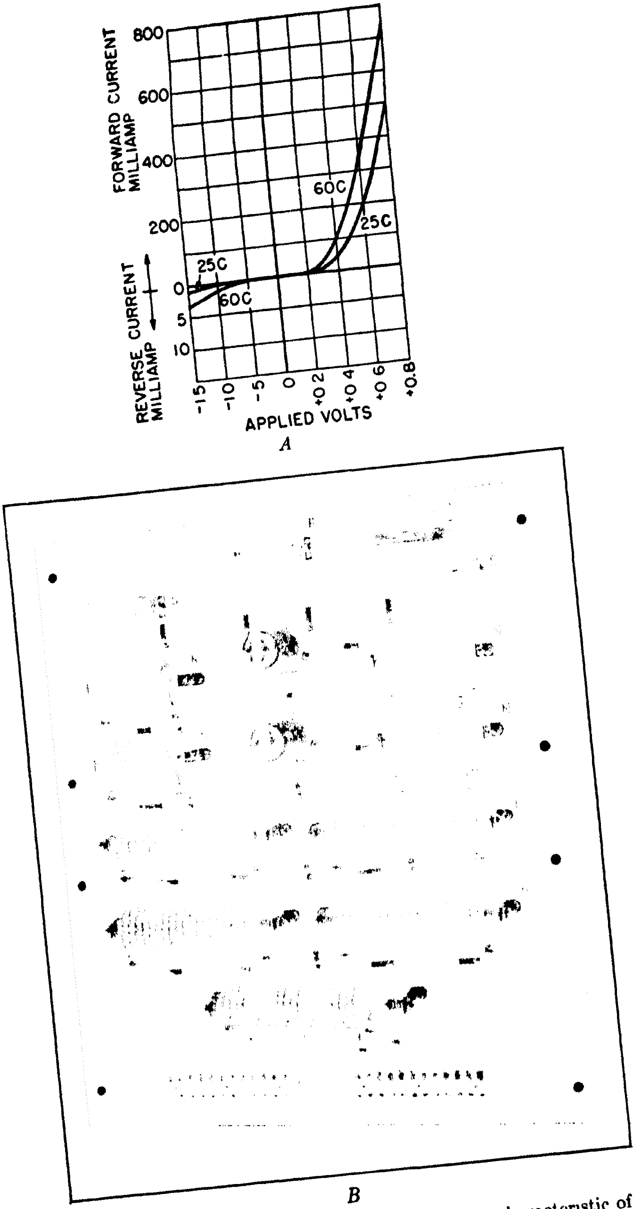
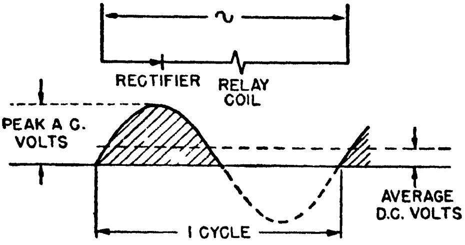
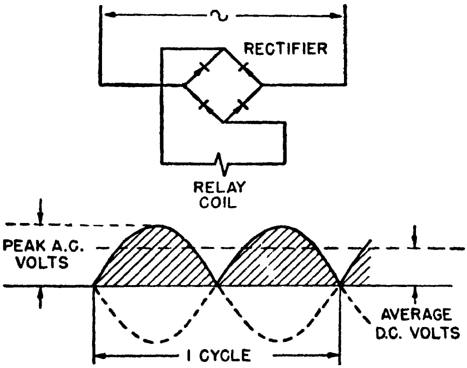


FIG. 140. Selenium rectifiers. *A*. Current versus voltage characteristic of a rectifier cell. *B*. Group of rectifier stacks mounted on control panel.

However, when circuits above 220 volts are involved, it is more economical to design the rectifiers for operation on 220 volts and to use small control transformers to step down the voltage. Unless proper precautions are taken, parallel operation of several rectifier units should be avoided if possible. Internal resistance of rectifiers varies somewhat, and if many parallel paths are provided, current may not divide evenly. Uneven current may lead to overloading of some stacks, causing cumulative failure. If a large number of contactors or relays on a controller are d-c operated from an a-c system, it is preferable to use several rectifiers rather than one large unit with many parallel paths.



A-HALF WAVE RECTIFIER



B-FULL WAVE RECTIFIER

Fig. 141. Commonly used rectifier circuits.

Two kinds of rectifier circuits are commonly used on controllers, half-wave and full-wave rectifiers. Their elementary connections and the wave shape of the resultant d-c voltage are indicated in Fig. 141. Sketch *A* shows a half-wave rectifier. A single path is provided for current to flow through the rectifier. In the symbol, the direction of current flow is indicated by the direction of the arrow, and the positive terminal of the rectifier is the one through which current leaves the rectifier and enters the load circuit. This convention agrees with commonly used polarity markings of d-c generators.

During each cycle of the applied a-c voltage, the positive half cycle appears as d-c voltage across the load and the negative half cycle is suppressed. The shaded areas in sketch *A* represent the d-c voltage. In order to determine the current, which flows in the load circuit, the average d-c voltage can be determined from the following formula:

$$E_{\text{dc(av)}} = 0.45E_{\text{ac(rms)}} \tag{59}$$

where $E_{\text{dc(av)}}$ = average d-c no-load voltage across load circuit,
$E_{\text{ac(rms)}}$ = rms a-c voltage applied to rectifier.

This formula does not include the drop through the rectifier, owing to load current in the d-c circuit. The voltage which actually appears across the relay coil is $E_{\text{dc(av)}}$ minus the drop in the rectifier, which, for a given load current, can be obtained from rectifier data published by the manufacturers.

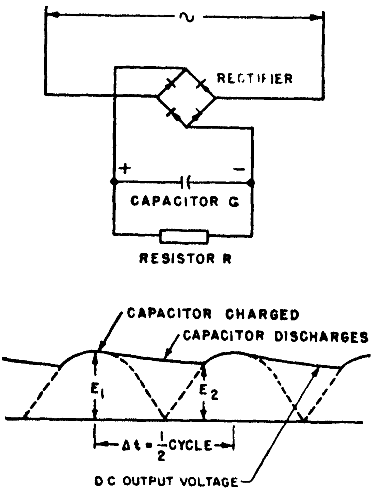


FIG. 142. Effect of capacitor on d-c output voltage of rectifier.

A full-wave rectifier is shown in sketch *B*. One stack with four paths, two stacks with two paths each, or four stacks are connected in a bridge circuit, and current flows in the d-c circuit during both half cycles of the applied a-c wave. The shaded area, designating the voltage across the d-c load, is twice as large as in sketch *A*, and thus the average d-c voltage is:

$$E_{\text{dc(av)}} = 0.90E_{\text{ac(rms)}} \tag{60}$$

The d-c output voltage is not smooth. It consists of a number of unidirectional pulses. It can be considered as an average d-c voltage, over which is superimposed an a-c ripple, the principal frequency of which is twice the frequency of the a-c power supply. On certain applications, for instance, when rectified d-c voltage is used as reference voltage in regulating circuits, it is desirable to reduce the amount of voltage ripple, that is, to "smooth out" the d-c voltage wave. It can be accomplished by connecting a capacitor in parallel with the d-c load. Refer to Fig. 142, which shows a full-wave rectifier feeding a resistor. The dotted half-sine waves represent the rectified d-c voltage that would appear across the load circuit if there were no capacitor. As the d-c voltage rises, the capacitor is charged, and full charge is determined by the peak a-c voltage. While the d-c voltage drops to zero, the capacitor is discharged through the load resistor, but the voltage across the load stays above the dotted sine wave. During the next half cycle the capacitor is fully charged again, and the cycle repeats. The circuit behavior described above occurs, of course, only if the load resistance is high so that the rectified voltage sine wave drops faster than the capacitor discharges.

To calculate a rectified d-c control circuit, it is necessary to determine the amount of capacity required to keep the variation in d-c voltage below a certain value. For low currents, that is, for high values of resistance R, the following approximate method of calculation can be used. Consider the capacitor discharge curve a straight line. The average d-c voltage is:

$$E_{\mathrm{dc(av)}} = \tfrac{1}{2}(E_1 + E_2) \qquad (61) \bullet$$

The average d-c current flowing through the resistor is:

$$I_{\mathrm{dc(av)}} = \frac{\frac{1}{2}(E_1 + E_2)}{R} \qquad (62) \bullet$$

During the discharge period of the capacitor, the current flowing through the capacitor is:

$$I_{\mathrm{dc(av)}} = \frac{C(E_1 - E_2)}{\Delta t} \qquad (63) \bullet$$

Time interval Δt can be taken as the duration of one half cycle in seconds. Then, in order to maintain voltage variation $\Delta E = E_1 - E_2$ at a given value, the following capacity in farads must be used:

$$C = \frac{(E_1 - \frac{1}{2}\,\Delta E)\,\Delta t}{R\,\Delta E} \qquad (64) \bullet$$

With a given capacitor, voltage variation ΔE increases with decreasing resistance or, in other words, with increasing current. With a given load circuit, voltage variation ΔE decreases with increasing capacitance.

The use of a half-wave rectifier as a blocking rectifier in a d-c control circuit is illustrated in Fig. 143. Let a rotating d-c machine serve as a source of d-c control power. It may be a tachometer generator, the polarity of which reverses with reversal of the machine to which it is connected. In the left-hand sketch the polarity is such that current flows through the rectifier and the relay coil. The relay is energized. In the right-hand sketch the polarity of the d-c source is reversed. The rectifier blocks the flow of current through the relay coil, and the relay is de-energized. Blocking rectifiers can be used in relaying circuits, the response of which depends on the polarity of the control signal received.

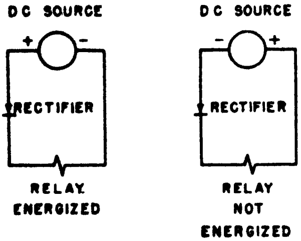


FIG. 143. Use of half-wave rectifier for blocking.

Voltage Regulators

In connection with controllers for d-c motors, especially adjustable-voltage systems, it is often desirable to regulate the output voltage of the exciter. The purpose is to establish a constant-voltage d-c control bus which can be used as a reference and remains constant while the load on the exciter varies between no load and full load. Voltage regulators vary the exciter field current as a function of the exciter output voltage so as to maintain a constant output voltage. The principal elements of a voltage regulator are:

1. A variable resistance element which is connected in series with the exciter field winding and permits varying the exciter field current.
2. A voltage responsive magnet, the coil of which is connected across the exciter voltage so that the pull of the magnet is a measure of the exciter voltage.
3. A reference, such as a spring, the tension of which opposes the pull of the magnet and which is so adjusted that it just neutralizes the magnet pull when the exciter voltage is at its desired value.
4. A mechanical linkage which causes the net pull of the magnet to vary the resistance of the variable resistance element when the exciter voltage deviates from its set value.
5. An anti-hunt feature, which prevents the regulator from overshooting, and consequently from hunting, when the regulator corrects the exciter field current.

In Fig. 144 are front and side views of voltage regulators embodying the elements described above. The variable resistance elements consist of loosely stacked carbon plates spaced apart in the middle by thin separators, forming a pivot for each plate. Silver buttons are inserted in the front end of the carbon plates. With the stack pressed down in front, a low resistance path is formed through the silver buttons. As the pressure is relieved in the front and applied in the back the stack tilts slightly. The silver buttons open, and more and more current passes through the carbon so that the resistance of the stack increases.

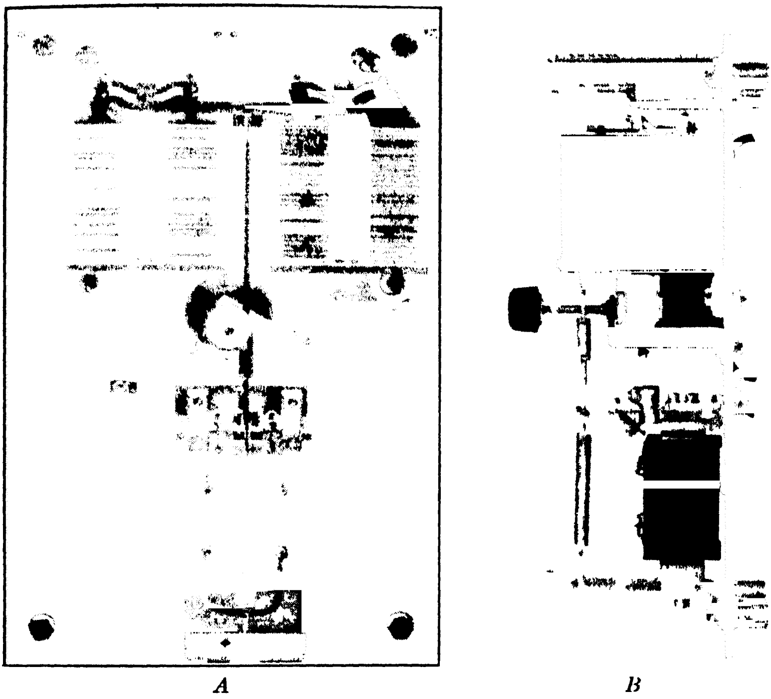

A *B*

FIG. 144. Voltage regulator. *A* Front view *B*. Side view

The magnet armature operates on a system of levers which vary the pressure on the front or back of the carbon stack and thus change the resistance of the stack as a function of applied voltage, proportional to the pull of the magnet. A calibrated spring opposes the magnet pull and determines whether the resistance of the carbon stack should be increased or decreased. A small rheostat is connected in series with the magnet coil to adjust the voltage at which the coil current is just sufficient to balance the spring tension. The adjusting rheostat setting determines the voltage that the regulator maintains.

Elementary connections of a d-c exciter with voltage regulator are indicated in Fig. 145. The regulator main coil is connected across the exciter terminals, and its current is proportional to the exciter voltage. The variable resistance element is connected in the exciter shunt field circuit, in series with the field rheostat. When the exciter voltage rises above the desired value, the resistance of the variable element is increased, causing the exciter field current to decrease. Conversely, when the exciter voltage drops below the desired value, the resistance of the variable element is decreased, causing the exciter field current to increase. The exciter field rheostat should be adjusted so that, with the regulator resistance element short-circuited, the exciter no-load voltage is 20 per cent above rated voltage.

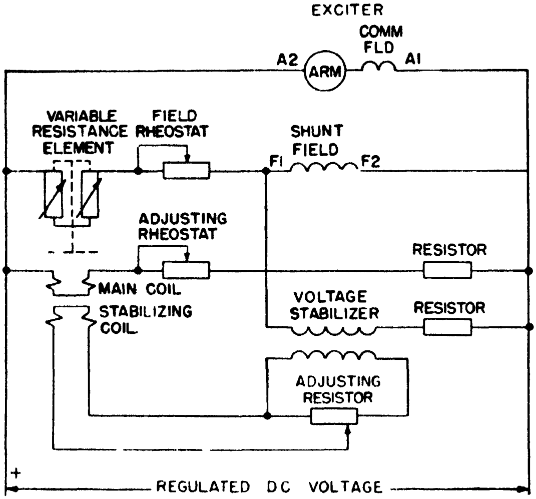


FIG. 145. Connections of exciter voltage regulator.

The anti-hunt feature is provided by a voltage stabilizer, which is in fact a d-c transformer. The primary winding, consisting of a large number of turns with high resistance, is connected in parallel with the exciter shunt field and measures the drop across the field. The secondary winding has fewer turns and lower resistance. As long as the exciter field current remains constant, no voltage is induced in the secondary winding of the stabilizer. However, when the field current changes, a voltage is induced in the stabilizer secondary winding. Its magnitude is proportional to the rate of change of the field current. The polarity depends on whether the field current increases or decreases. This induced voltage is loaded into a resistor. An adjustable portion of the voltage drop across the resistor is fed into the stabilizing coil, which is also located on the operating magnet. The stabilizing coil opposes the main coil. The pull developed by the stabilizing coil is a function of the rate of change of field current, and the direction of the pull depends on the direction of field current change. This prevents overshooting of the regulator.

Although a specific design of voltage regulator has been described as an example, there are other designs on the market which differ in mechanical details and in the method employed to vary the resistance in series with the exciter field. Voltage regulators have also been applied to d-c shunt motors to control the motor field current as a function of armature current or speed. If resistance is connected in series with the motor armature and the voltage drop across the resistance is used to energize the regulator coil, the motor armature current can be held constant. Connecting the regulator coil across the terminals of a tachometer generator permits holding motor speed constant.

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CHAPTER 7

PILOT DEVICES

Pilot devices are control devices, the contacts of which are connected in control circuits. They in turn operate magnetic contactors or other remote-operated devices which handle the power circuits. The common feature of pilot devices is that they are mechanically operated, which sets them apart from relays and other magnetically operated control devices. Pilot devices may be under the manual control of operators, such as push buttons and master switches; they may be operated automatically by conditions of pressure, temperature, or liquid level; or they may simply be actuated by the mechanical motion of the motor or the drive. In this category fall plugging and limit switches.

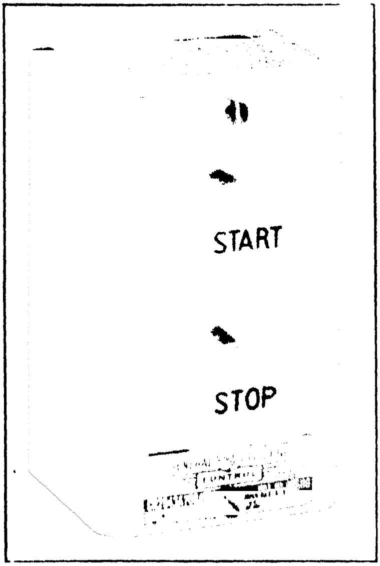


FIG. 146. Typical standard duty push button station with cover, for wall mounting.

Push Buttons [1]

Push buttons are the most frequently used type of manually operated pilot devices. They consist of a single or double break contact unit connected to a plunger, usually made of insulating material, which, when depressed, actuates the contacts. According to function, there are two types of push buttons, with momentary contact and maintained contact. A momentary contact push button stays in its depressed position as long as the push button is held depressed. When the push button is released, a spring returns it to the original position. A maintained contact push button contains a snap action mechanism, and two buttons are necessary for its operation. When one button is pressed, the push button contacts snap closed or open, and when the button is released, the contacts stay in that position. A second button must be pressed to reset the contacts.

According to contact capacity, there are two classes of push buttons, designated as standard duty and heavy duty. Standard duty push buttons are designed for moderate amounts of control current; heavy duty push buttons are able to handle higher control currents. Typical ratings of a line of standard duty and heavy duty push buttons are listed in Table 10. The current values given for breaking apply to inductive circuits, and they should be used as a basis for selecting push buttons which have to interrupt coil circuits of contactors.

TABLE 10

CURRENT RATING OF A TYPICAL LINE OF PUSH BUTTONS

	Make All Voltages	Carry Cont	Interrupting Rating						
			D-C Inductive at Volts			A-C Inductive at Volts			
			115	230	550	110	220	440	550
Standard Duty									
Double break contacts	30	10	1.5	0.7	0.2	30	20	7	5
Single break contacts	30	10	1.0	0.3	0.1	30	20	4	3
Heavy Duty									
Double break contacts	50	10	2.0	1.0	0.4	50	30	8	6
Single break contacts	50	10	1.0	0.3	0.1	30	20	4	3

A typical standard duty push button station is shown in Fig. 146. The momentary contact push button units are enclosed in a sheet metal case, the front of which is removable to permit wiring. The case is arranged for wall mounting. Guards in the cover prevent inadvertent pressing of the buttons. The unit shown has a normally open start button, the contact of which closes when the button is pressed. The stop button is of the normally closed type. The contact opens when the button is pressed. The designation of push button functions is molded in the face of the button. Stations are obtainable with one, two, or three buttons.

For use on machine tools, a standard duty push button unit of oil-tight design is available. It is illustrated in Fig. 147. A gland around the button prevents oil from entering the interior of the unit and keeps the contacts clean when the button is pressed by an operator with an oil-soaked glove. The unit requires only one hole for mounting, and it is suited for flush mounting on a plate which can be assembled over a cavity in the machine tool frame. The function of the push buttons is designated by name-plates over the buttons.

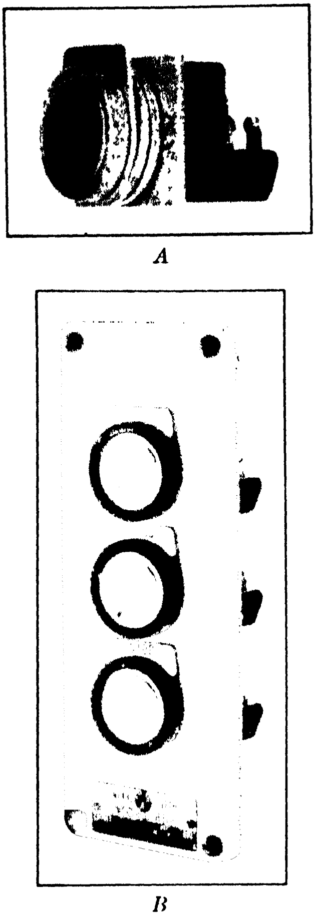


FIG. 147. Standard duty oil-tight push buttons. *A* Individual push button unit. *B*. Three-button station for flush mounting

Heavy duty push buttons have larger contacts. The contact units are equipped with two sets of contacts, one normally open and one normally closed. When the button is pressed, the normally closed contact opens before the normally open contact closes. The normally closed "back contacts" can be used for interlocking purposes, which is of importance in connection with reversing controllers. Push button units may be assembled in cases for wall mounting or they can be assembled on escutcheon plates suitable for flush mounting. Up to five push buttons can be mounted in one station. For a push button a turn button selector switch or an indicating light may be substituted. Shown in Fig. 148 are component units and complete stations both for surface and flush mounting.

For use in dusty or wet locations, push buttons are enclosed in watertight cast cases with gasketed cover (see Fig. 149). The push button units are assembled in the box. A paddle-shaped lever in the cover, which is connected through a stuffing box to a treadle-shaped lever on the outside, serves to depress the buttons. The push button unit in the illustration is of the maintained contact type. The lever mechanism tying the two buttons together can be seen. When one button is pressed, the other button is pushed out. The station shown contains two indicating lamps. In their place, another two button push button unit could be used in the same box.

Foot-operated push button stations permit an operator to control his machine by movement of his feet while his hands are free to perform other tasks. The station in Fig. 150 has push button units in a heavy cast case, and the buttons are actuated by a foot-operated treadle lever.

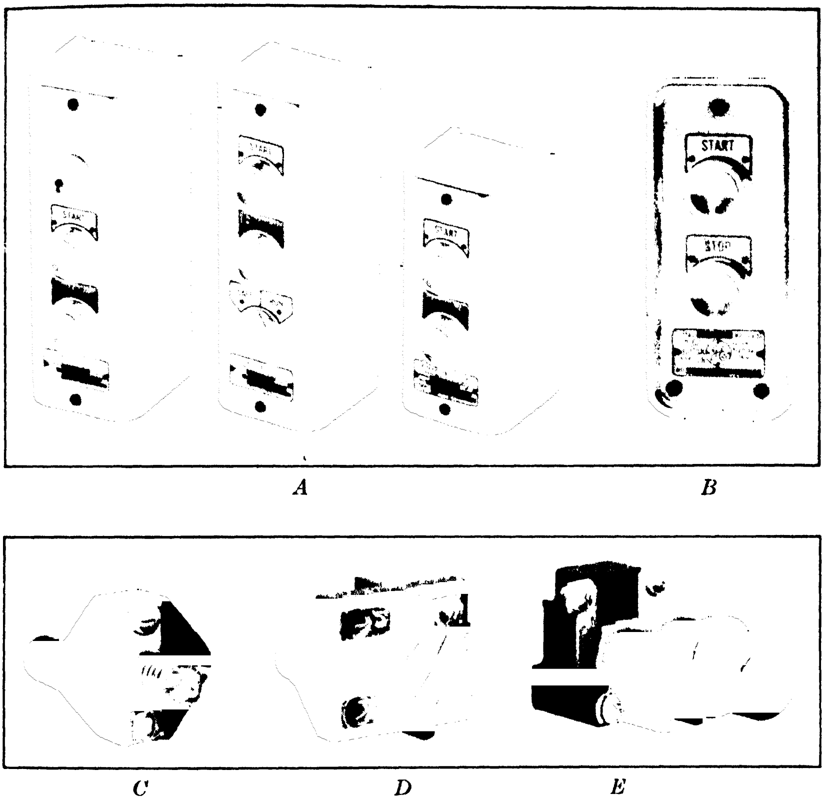


FIG. 148. Heavy duty push buttons. *A* Wall-mounted stations. *B*. Flush-mounted station. *C*. Indicating light. *D*. Turn button unit. *E*. Push button unit.

Installations in hazardous atmosphere, with either explosive gas or inflammable dust present, require enclosures which prevent the arcs formed upon contact opening from igniting the surrounding atmosphere. One way to prevent arcing from starting an explosion is to

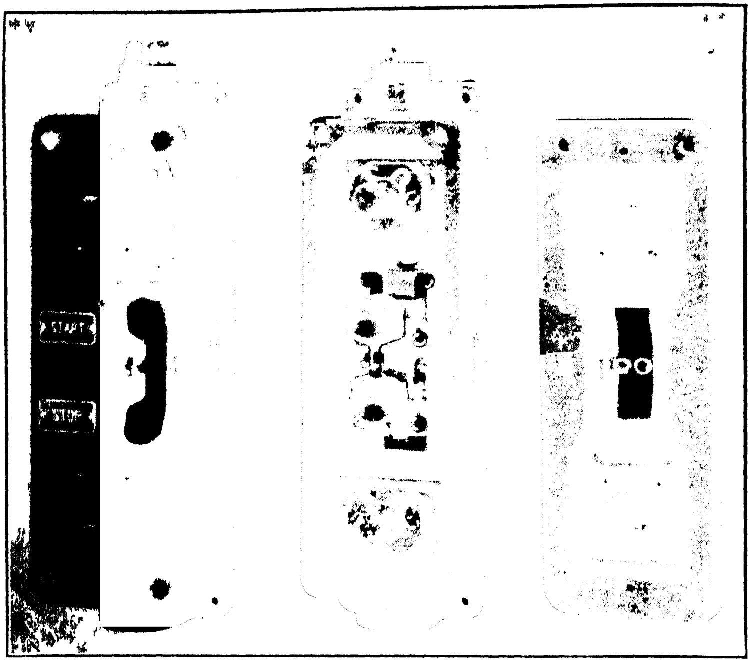


Fig. 149 Heavy duty push button station with watertight and dust-tight case

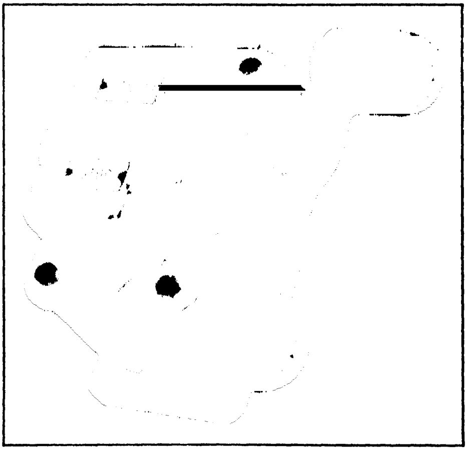


Fig. 150 Foot treadle operated push button station

arrange the contacts under oil. Another method is to enclose the contact unit in a special box with wide flanges. Both methods of making a push button station explosion-proof are acceptable. Typical explosion-proof push buttons are shown in Fig. 151.

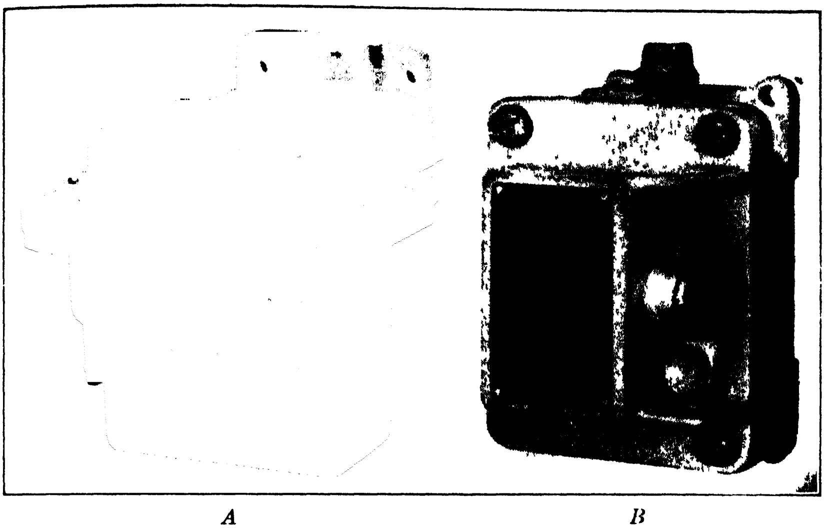


FIG. 151. Explosion-proof push button stations. A. Oil-immersed. B. Air-insulated.

Master Switches [1]

Master switches are manually operated control switches, designed to operate the coil circuits of magnetic controller. In that respect, their function does not differ from push buttons. However, whereas a push button usually contains only one or a pair of contacts which are either open or closed, master switches contain a multiplicity of circuits, which open and close in a definite sequence. Master switches provide greater flexibility, and a greater variety of functions can be performed by one switch. The contacts are operated by a shaft, which is turned by the movement of a lever.

A simple master switch design is obtained by using a cylinder or drum, on which conducting segments are arranged, sliding under stationary brushes or contact fingers. Shown in Fig. 152 is a drum type master switch which was developed originally for shovel service. Copper segments slide under carbon brushes. The shaft is mounted in ball bearings. A gasketed cast cover encloses the switch and prevents entrance of dust and dirt. The principal advantages of this type of switch are its compactness and the ease with which it can be operated. Its disadvantage is lack of flexibility both in the number of circuits and in the contact closing sequence.

Another advantage of the drum type construction is the large number of control points which can be realized. A typical switch of that type is shown in Fig. 153. This switch has forty-seven positions. A copper drum slides under stationary contact fingers. This type of switch is used to short-circuit resistance steps in the generator field circuit of adjustable-voltage systems, the generator power circuit being controlled by contactors. The large number of control points insures smooth acceleration and deceleration of the motor controlled. The handle moves in a vertical plane and drives the drum through a bevel gear.

FIG. 152. Drum type master switch with cover removed.

The necessity of arranging contact segments on the drum in a definite pattern makes it difficult to make up an irregular contact closing sequence, especially if the sequence in one direction of rotation is different from that in the other direction. After a switch has been built, it is often impossible to change the contact closing sequence if control operation is to be changed after the equipment has been installed. A complete new drum must then be used. Another disadvantage of sliding contacts is the slow motion with which the contact finger and the segment part when the circuit is opened. This delay causes burning of the edges of the segments so that the segments must be renewed often on frequently operated master switches.

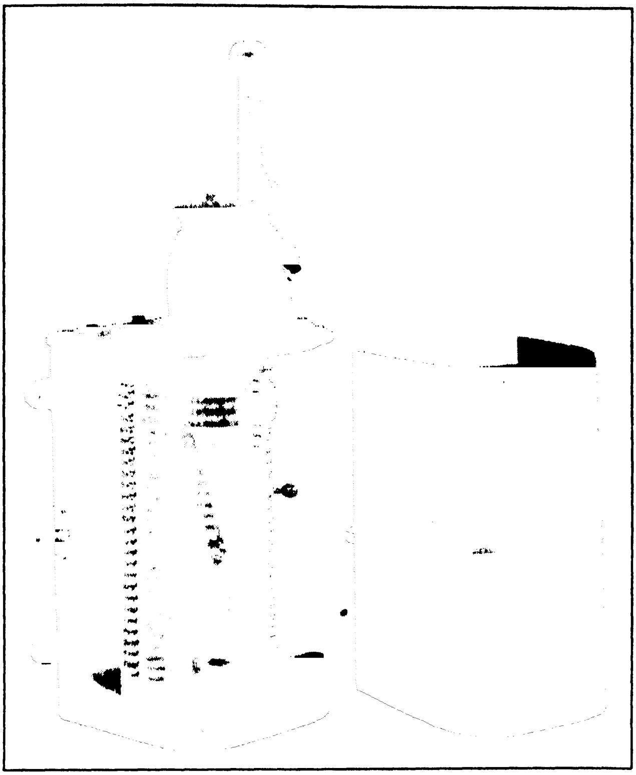


FIG. 153. Drum type 47-point master switch for field control of adjustable-voltage system.

These disadvantages are avoided by cam type master switches. Movable butt type contacts, which close against stationary contacts, are mounted on a pivoted support, the motion of which is governed by a cam fastened to the master switch shaft. Turning the shaft rotates the cam and closes or opens the contacts in any desired sequence between switch positions. This arrangement is extremely flexible. If a change in the closing sequence of a contact is desired after the switch has been built, it can be made easily by exchanging a cam or even by cutting the cam to a new contour. A typical cam type master switch is illustrated in Fig. 4, together with the method used to indicate contact closing sequence symbolically. A master switch with a larger number of circuits is shown in Fig. 154. The left illustration is a switch with sheet steel cover in place. The right one shows details of the contact arrangement and the method of making connections to the terminals. To reduce friction, small ball bearings are used as rollers for moving the contact arms. A starwheel and pawl mechanism provides a stop in each master switch position so that the operator may feel each position. It also prevents the handle from drifting if the master switch is left in a position out of neutral. If desired, a spring return mechanism can be included which returns the master switch to the neutral position when the handle is released. The addition of spring return makes the master switch harder to operate, and spring return to neutral is practicable only for a limited number of circuits and switch positions.

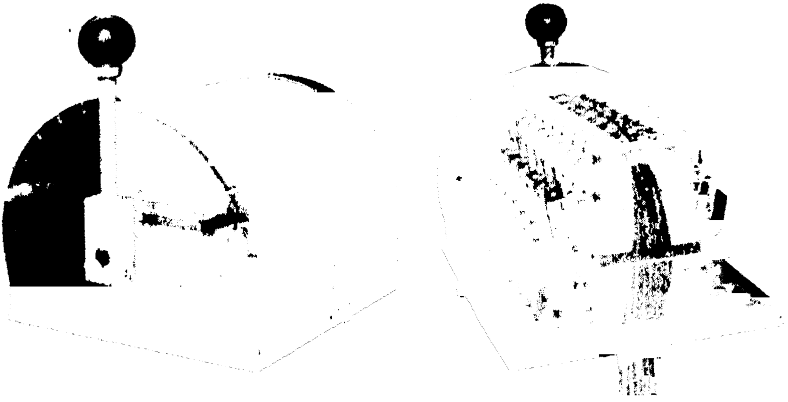

A B

FIG. 154. Cam type master switches. *A*. With cover. *B*. Cover removed.

Although the master switches described are typical and embody the essential elements required of such switches, a variety of different sizes and designs is on the market. A multitude of handles can be obtained to suit individual operators' requirements. Special enclosures can be used in places where the master switch must be dust-tight, watertight, or explosion-proof. Switches with special shaft extensions are available for control desk mounting. Foot mechanisms permit an operator to keep his hands free while operating switches with his feet.

When a number of master switches are to be mounted on a panel or on a control desk, the required space and neatness of appearance are important. A typical master switch design for desk or panel mounting is illustrated in Fig. 155. Although the construction is lighter and the contact rating is lower than in the previously described switches, this design is ideally suited for applications requiring the operator to control a large number of drives from one central control point.

FIG. 155. Small master switch for panel or control desk mounting.

Pressure Switches

Pilot devices discussed so far are used by an operator to start, stop, and adjust a motorized drive. There is also a need for devices which start and stop a motor automatically as a function of the condition of some medium, such as air or a liquid. For instance, an air compressor is started when the pressure in an air system drops below the desired value, and the compressor is stopped when the pressure is built up again. Another example is an accumulator pump which starts and stops as a function of water pressure in the accumulator tank.

Pressure switches are used to actuate magnetic contactors which start and stop the motors, or they may control small motors directly. A pressure switch contains a diaphragm which forms one wall of a pressure chamber. The other side of the chamber is piped to the system the pressure of which is to be controlled so that one side of the diaphragm is under the pressure of the system. The other side of the diaphragm is mechanically connected to a compression spring the tension of which can be adjusted so that its force on the diaphragm balances the force exerted by the system pressure. If the system pressure is above or below the spring setting, the diaphragm deflects and, through a lever mechanism, opens and closes a contact. Figure 156 shows a typical pressure switch. When the pressure rises above the switch setting, the contact opens. When the pressure drops below the setting, the contact recloses. The switch setting can be adjusted by turning the screw which determines the compression of the spring.

Pressure switches can be obtained for contact opening between 1.25 and 5000 pounds per square inch. The range over which any individual switch can be adjusted varies approximately between 10 to 1 and 3 to 1. Switches with a large diaphragm and a weak spring can be used to measure the pressure of a vacuum system. Standard switches are available for a range of adjustment between 3 and 26 inches of mercury. The nature of diaphragm-operated devices demands that there be a definite differential between the pressures at which the contacts open and reclose. This differential varies somewhat with different types of switches, and on a given switch it increases with increased pressure setting. The pressure at which contacts reclose is generally between 65 and 90 per cent of the pressure at which contacts open. This differential is generally not adjustable.

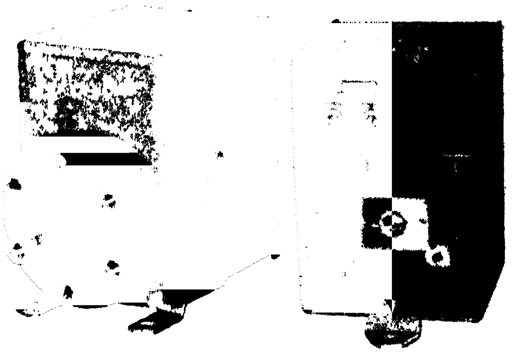
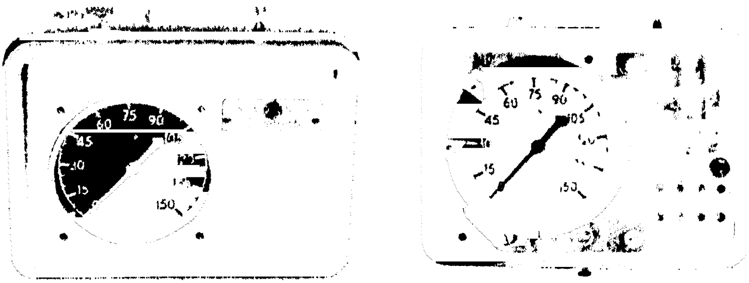


FIG. 156 Pressure switch *A* Back view showing diaphragm. *B* Front view showing contacts and spring

Contact operation can be inverted. Switches which close their contacts upon a rise in pressure and reopen on a drop in pressure are built for special purposes.

Pressure governors can be adjusted more accurately, and they operate on an adjustable pressure differential. See Fig. 157. A pressure governor is essentially a gage which measures pressure by the deflection of a Bourdon tube. Actual pressure measured is indicated on a scale. The deflection of the tube actuates a set of delicate contacts which in turn operate an auxiliary relay. The relay coil circuit is arranged like that of a thermostatic relay (see Fig. 126) so that the governor contacts make but do not break current. The pressure at which the auxiliary relay contacts open and close is adjusted by riders on the scale. Governors are built for scale ratings between 15 and 10,000 pounds per square inch. Operating pressures can be set between 20 and 80 per cent of full scale. The minimum differential between contact opening and contact closing is 2 per cent of full scale.



A *B*

FIG. 157. Pressure governor. *A*. With cover. *B*. Cover removed.

Float Switches

In automatic pumping stations the pump motors are started and stopped automatically so as to maintain a definite water level. Pilot switches are operated by floats, the position of which is determined by the water level. The float actuates the switch through a rod or a chain. In Fig. 158 is shown a typical chain-operated float switch. One end of the chain is connected to the float and the other end to a counterweight. Stops connected to the chain move a lever which turns and tilts a mercury tube forming the switch contact. When the water level raises the float, the switch contact opens. When the water level drops and the counterweight rises, the switch contact recloses.

The differential in water level between contact opening and contact closing can be adjusted over a wide range. A minimum differential must be maintained in order to obtain sufficient travel to turn the switch-operating lever. The differential may be increased at will, the only limitation being the available length of chain. For large pumping stations involving a multiplicity of pumps which are to be started and stopped in a definite sequence at various water levels, multi-circuit float switches have been developed They are built as rotary switches, similar to master switches, and the switch shaft is driven from the float chain through a sprocket. The contacts are adjustable so that they open and close at various water levels.

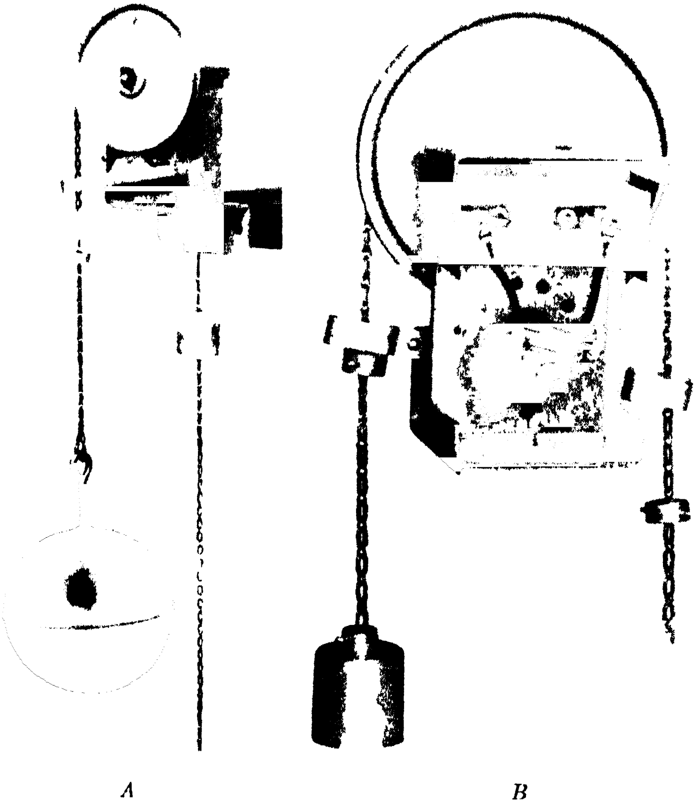


FIG. 158. Chain-operated float switch. A General view B Details of contacts

Thermostats -, 3

Many magnetic controllers have the purpose of maintaining temperature. A cooling water pump for carrying away heat generated during a manufacturing process may be started and stopped to maintain a certain temperature for the process. The heating elements of an electric furnace may be switched on and off to maintain a constant temperature inside the furnace.

Many devices are on the market to measure and record temperature. Although they are primarily designed as instruments and incorporate a high degree of accuracy, they are sometimes used as pilot devices, especially for the control of electric furnaces. They measure temperature by means of a thermocouple or by a resistance thermometer. The emf of the thermocouple or the resistance change of the thermometer is used in a bridge circuit to balance a galvanometer against the voltage of a standard cell. A small motor moves a potentiometer forming part of the bridge circuit, to balance the galvanometer and to actuate the control contacts. As the contacts are delicate and unsuited to break current, a thermostatic relay is used (see Fig. 126). Such temperature controllers are essentially precision instruments of a special nature, and a discussion of their details is considered be-

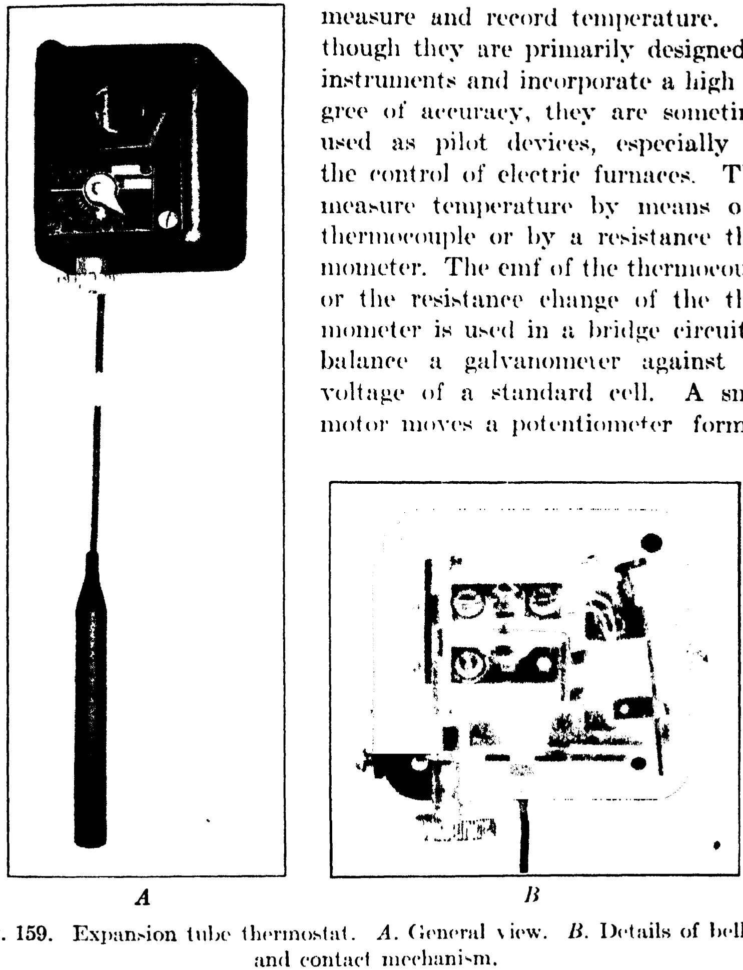


FIG. 159. Expansion tube thermostat. *A*. General view. *B*. Details of bellows and contact mechanism.

yond the scope of this book. The reader who is interested in high-accuracy temperature devices should refer to special literature on that subject.

Temperature-sensitive devices which do not indicate and record temperature but are used as pilot devices to provide control impulses are called thermostats. They open or close contacts at a certain temperature, thus actuating magnetic contactors. Various principles are used to obtain response to temperature, such as the unequal expansion of rods made of different material, the deflection of a bimetallic strip, or the expansion of a liquid or a gas.

A typical thermostat for industrial control use is illustrated in Fig 159. A sealed-off tube is filled with a liquid. A bellows at the end of the tube expands when the liquid expands with rising temperature. The pressure of the liquid on the bellows is balanced against an adjustable spring. When the bellows pressure overcomes the spring pressure, a contact opens. When the bellows pressure drops below the spring pressure, the contact recloses. Depending on the size of the tube and the liquid used, the operating range of a given thermostat varies. Within its range, the contact-opening temperature can be adjusted by varying the spring pressure.

The temperature range of a given thermostat is limited. It may vary between 1 to 4 and 1 to 1.15, depending on tube size and the nature of the liquid. Thermostats as shown in Fig. 159 are available for operation at temperatures between 30 and 750 F. The temperature differential between opening and reclosing of the contact is a constant number of degrees for any thermostat. Depending on the temperature for which the thermostat is designed, the differential may vary between 4.5 and 20 F. When applying thermostats, it is necessary to install them in such a manner that there is a good heat transfer to the tube of the thermostat. The liquid and the tube have a definite thermal capacity so that there is a time lag between the change in temperature outside the tube and the response of the thermostat. Good thermostat design aims to speed up the response as much as possible, but proper installation is always an important factor.

Switches Responsive to Motor Rotation

Speed switches and speed governors respond to a definite speed of either the motor shaft or some shaft of the driven machine. A centrifugal mechanism opens or closes contacts at a definite speed. Such switches are used to provide a control impulse and to start a control sequence when the motor speed reaches a given value. For instance, a speed switch can be used to close the low-speed winding of a two-speed squirrel cage motor, after the motor has decelerated to a speed close to the synchronous speed of the low-speed winding. Speed switches are used as overspeed protective devices. Their contacts open when the motor speed exceeds a safe value, disconnecting the motor from the line and shutting down the equipment.

Figure 160 illustrates a typical centrifugal speed governor, with cover removed, to expose details of internal construction. A set of weights which move outward under the influence of centrifugal force actuate a toggle mechanism, which in turn causes the contacts to open or close. Two sets of contacts are provided, either of which may be normally open or normally closed. The speed at which the switch operates is determined by the size of the weights and by the spring. Adjustment of the speed setting within the range of the switch is possible by changing the spring pressure. For any given combination of spring and weights, the differential between speeds at which contacts operate and reset varies between approximately 10 and 40 per cent of the operating speed, depending on the spring adjustment.

FIG. 160. Centrifugal speed governor (Courtesy Cutler-Hammer, Inc.)

Another control problem which arises frequently is determining whether the motor is at rest or whether it turns in either direction. Switches for this purpose are used mostly on automatic plugging controllers, the circuit details of which are discussed in Chapters 11 and 12. A plugging switch, as shown in Fig. 161, consists of a housing in which a permanent alnico magnet rotates. The magnet is coupled to the motor shaft and rotates at motor speed. An aluminum cup is arranged between the magnet and the housing so that the cup may turn. When the magnet rotates, eddy currents are induced in the aluminum cup, and torque is developed which turns the cup in the direction that the magnet rotates. The motion of the cup causes either one of a pair of contacts to close. When the motor is at rest or turns at slow speed, the contacts are open. When the motor turns faster than some minimum speed in either direction of rotation, one contact or the other is closed.

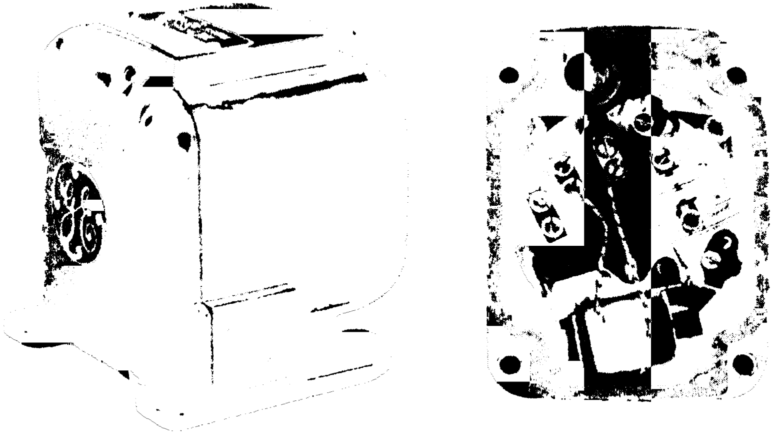

A *B*

FIG. 161. Plugging switch. *A*. General view. *B*. With cover removed.

The switch is suitable for speeds up to 1800 rpm, and the contacts open when the speed drops to a value which can be adjusted between 750 and 40 rpm. Speed adjustment is made by varying the tension of the springs which restrain the contact movement. On certain applications it is desirable, for safety reasons, to prevent the contacts from closing when the motor is rotated by hand. Otherwise the line contactor may be closed inadvertently. A magnetically operated lock-out which permits the contacts to close only when the motor power circuit is energized may be provided as an optional item.

Track Type Limit Switches [1]

Limit switches, among the most widely used pilot devices, are actuated by the travel of the driven machinery. They may slow down and stop the drive at the ends of the travel, interlock between various drives, or provide control impulses to initiate a control sequence as a function of the position of the driven piece of machinery. Limit switches are divided into two categories, depending on how they are operated mechanically by the drive. Track type limit switches are tripped directly by cams, levers, push rods, and the like, attached to some part of the machine. Either the switch is stationary and actuated by some moving member or the switch moves with the machine and is actuated by a stationary member. Geared type limit switches are mounted stationary, and a geared or directly coupled shaft rotates with the drive shaft. Thus the rotation of the switch shaft is a replica of the travel of the drive, and contacts can be arranged to operate at any desired point of travel.

Shown in Fig. 162 is a typical small and compact track type limit switch with roller lever designed for standard duty. It is used on machine tools and general-purpose applications. It controls small and medium-size contactors and is installed where dust and dirt conditions are not severe. Its overtravel is limited, and it should be used only where the moving member, actuating the switch, is well guided. It contains snap-action contacts so that the contact opening speed is independent of the speed with which the switch is tripped mechanically. One normally open and one normally closed circuit are available. When the operating lever is released, the switch is returned to its original position by spring action.

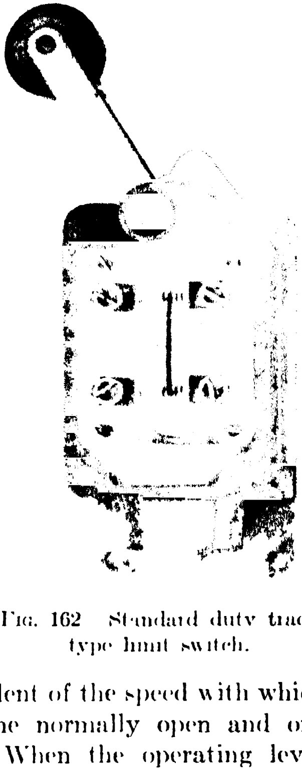


FIG. 162 Standard duty track type limit switch.

Heavy machinery applications, such as material-handling equipment, hoists, conveyors, steel mill auxiliaries, and the like, demand a heavier type of limit switch, as shown in Fig. 163. The actuating lever turns a cam shaft which operates two contacts, either one of which may be normally open or normally closed. Contacts can be made overlapping or underlapping. Contact operation may be set for spring return or non-spring return. The switch is enclosed in a *heavy case, which can be either dust-tight or watertight, so that the switch may be installed in wet and dirty locations.*

To provide for accurate positioning, for instance to seat a movable bridge span, plunger-operated limit switches are used. Such a switch

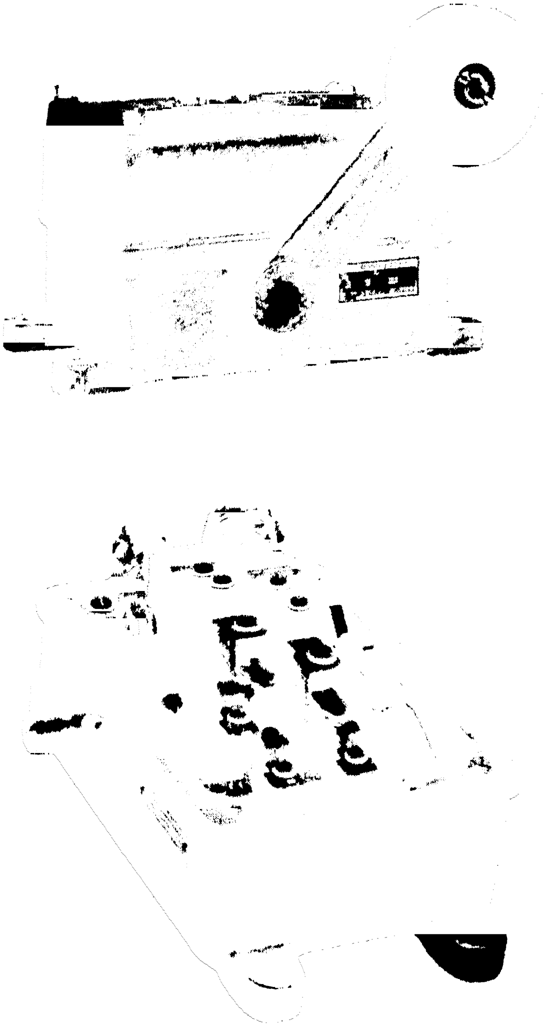


FIG. 163. Heavy duty track type limit switch. *A*. General view *B* With cover removed

is shown in Fig. 164. A plunger mechanism actuates a toggle, which in turn operates the switch contacts with snap action. A plunger movement of ¼ inch operates the switch. An overtravel of 2¼ inches is available after the switch has tripped. The contacts reset within ⅛ inch of the tripping position.

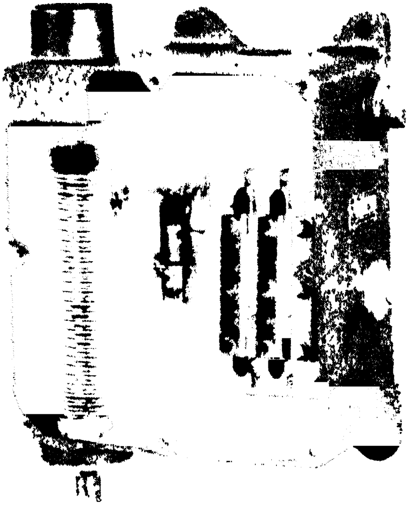


FIG. 164. Plunger-operated limit switch.

Geared Limit Switches

Geared limit switches translate the motion of the machine into the rotation of a shaft and use this rotary motion as an image of the distance actually traveled by the machine. For the application of geared limit switches it is necessary that there be a positive drive between motor and machine through gears or chains, with no slippage.

High accuracy of adjustment is obtained with lead screw type switches (see Fig. 165). Switch *A* is a small and inexpensive switch with a contact at either end of the machine travel. Gear wheels move laterally on the lead screw until they engage with the fixed gear wheels, which in turn operate the contacts. Adjustment of the tripping points is obtained by turning the movable gear wheels by hand away from the fixed gear wheels until the number of turns of the lead screw, necessary to trip the contacts, corresponds to the desired machine travel. Switch *B* is a larger switch which obtains contact operation not only at the ends of travel but also at intermediate points. Bars on the lead screw nut, arranged at different levels, trip contact units which are assembled on a horizontal bar.

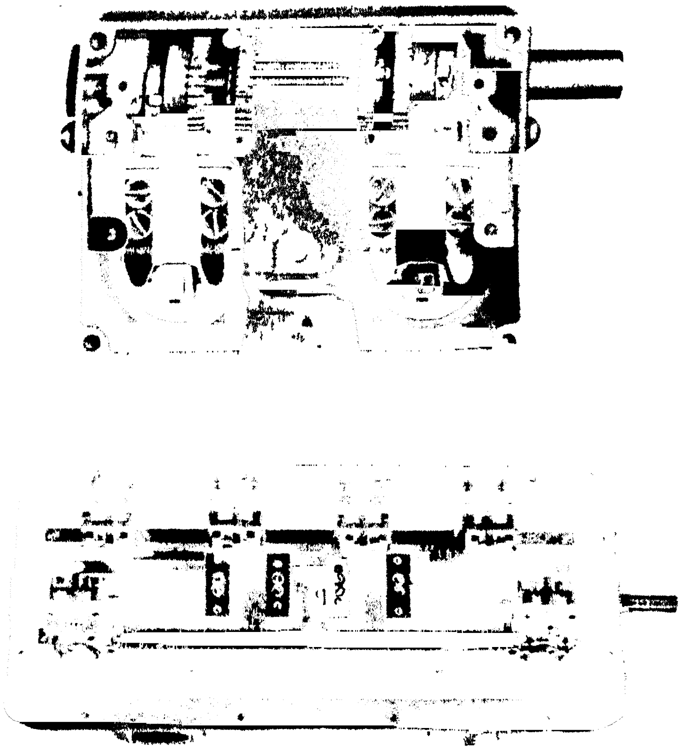
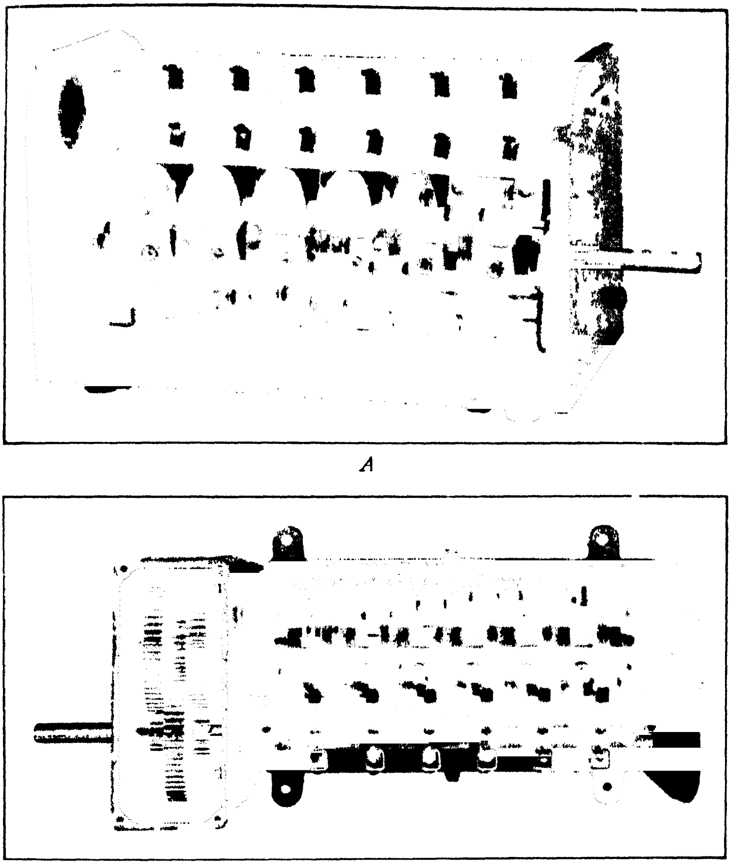

B

FIG. 165. Lead screw type geared limit switches. *A* Contact operation at ends of travel only. *B* Contact operation at any point of travel.

Adjustment of contact operation is obtained by sliding the contact units along the supporting bar to the proper position.

Lead screw type limit switches can be used only on reversing drives. Certain applications, for instance rotary car dumpers, involve travel in one direction only, with limit switch operation repeating itself once every operating cycle. This problem can be solved by using rotating cam type limit switches as shown in Fig. 166. A series of contacts is provided, and to each contact belongs a round cam which is clamped to the switch shaft. Adjustable closing and tripping dogs actuate the switch contacts. By changing the position of the dogs on the cams, contact operation can be set for any point of machine travel. When used with machines running in one direction only, a switch travel of 360 degrees corresponds to one operating cycle of the machine.


A

B

Fig. 166. Cam type geared limit switches. *A* For direct coupling. *B* With built-in reduction gear.

Cam type limit switches can also be used on reversing drives. To obtain best accuracy, the angular switch travel corresponding to the distance of travel of the machine should be chosen as high as possible, but not to exceed 340 degrees, in order to avoid interference of tripping dogs at the end of the travel. Cam type limit switches can be obtained either for direct connection to the machine or with built-in reduction gear.

Power Type Limit Switches.[6]

Power type limit switches are not pilot devices in the strict sense of the word. They do not control contactors, but they handle power circuits directly. However, since they are often used in connection with magnetic control to obtain functional results similar to those obtained by pilot type limit switches, they are included in this chapter.

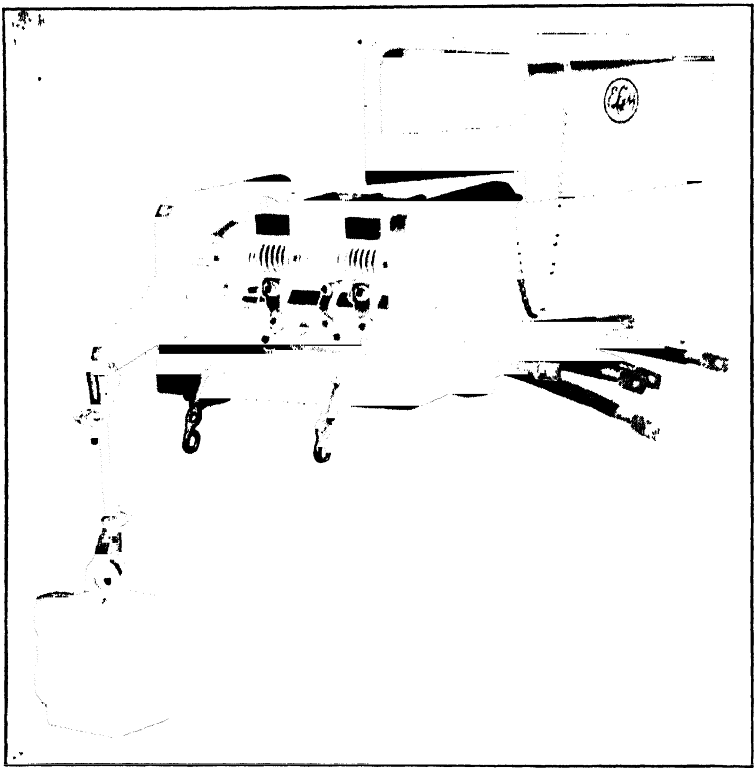


FIG. 167. "Youngstown" power type overhoist limit switch. (Courtesy The Electric Controller & Manufacturing Co.)

Power type limit switches are used principally on cranes and hoists, to obtain overtravel protection in the hoisting direction. The contacts are heavy enough to carry motor current, and magnetic blowouts are provided for interruption of current. By opening the motor circuit directly, instead of through contactors, a greater degree of safety is obtained, which warrants the higher cost of this type of limit switch where failure of any component part of a magnetic control system may result in serious material damage or injury or loss of life.

A typical power type overhoist limit switch for crane hoists is illustrated in Fig. 167. The switch contacts, which carry motor current, are held closed by a weight. When the hoist hook block travels beyond the extreme hoisting position the weight is raised by the block and the limit switch is tripped. The hoist motor is disconnected from the line, and an emergency dynamic braking circuit is established. Refer to Chapter 18 for a complete hoist controller diagram, including a power limit switch.

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CHAPTER 8

ELECTRONIC DEVICES

During the past decade electronic control has become such a broad subject that it is impossible to do it justice in one chapter. It is not considered the province of this book to present a treatise on electronic control. The reader who is interested in that subject should turn to a text on electronic phenomena and their use in industrial applications. Electronics has ceased to be mysterious and the specialty of a selected few. Practically all industries have become acquainted with electronic devices and use them in one form or another, and the day is approaching when the average electrical engineer will consider electronics as just another tool to be used in its proper place.

It is the author's opinion that electronic control will not supersede and eliminate magnetic control. However, electronic devices, as they are capable of performing tasks which cannot be performed by conventional magnetic devices, will become more and more interrelated with magnetic control and will complement the conventional devices at the disposal of the control engineer. It is the purpose of this chapter to present some of the simpler electronic devices which have found use in conjunction with magnetic control. No attempt is made to explain the principles of electronics and the characteristics of tubes. Many good textbooks are available on this subject.

Electronic Relays

Conventional magnetic relays require an amount of power for their operation which is measured in watts. Delicate contact-making measuring devices often do not have sufficient contact capacity to handle that amount of power. The resistance of a pilot contact actuating a magnetic relay must be so low that the drop across the contact does not reduce the voltage across the relay coil terminals below the pick-up value of the relay. Electronic relays require only milliwatts or a fraction thereof, and under adverse conditions they may be used as pilot devices for magnetic controllers. Contact resistance of the actuating device, such as a contact-making instrument, may be of the order of many thousand ohms and still operate an electronic relay satisfactorily.

In Fig. 168 is shown a typical electronic relay. It consists of a 6SN7GT twin triode tube, an anode transformer, a telephone type relay, several resistors and capacitors, all assembled in a weather-resisting enclosing case. An a-c power supply of 115 volts or 230 volts is required. The electronic tube is the equivalent of two separate triodes contained in a common envelope. The electronic tube controls the telephone relay which has a contact interrupting capacity of one ampere alternating current and can thus be used as a pilot device for a magnetic controller. The relay can be actuated by contacts having a resistance of 500,000 ohms or less. Since the contacts of contact-making instruments are usually of very light construction in order not to impair the accuracy of the instruments, they are likely to bounce. Therefore, a small time delay is built into the relay which prevents it from chattering because of contact bounce.

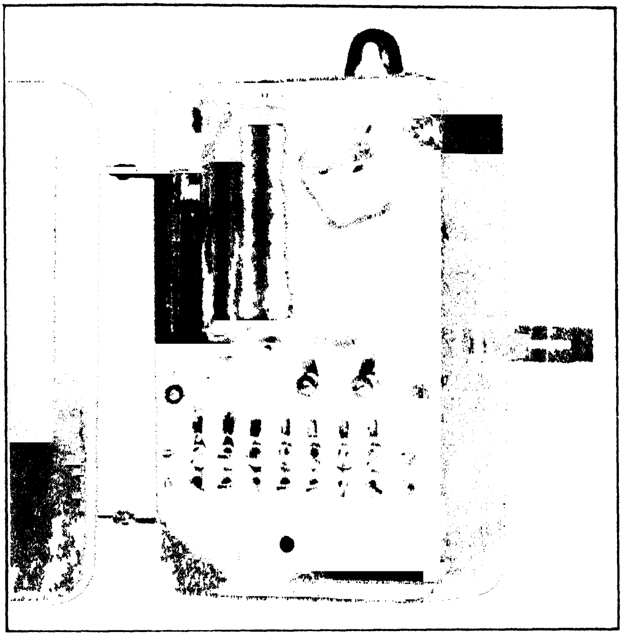
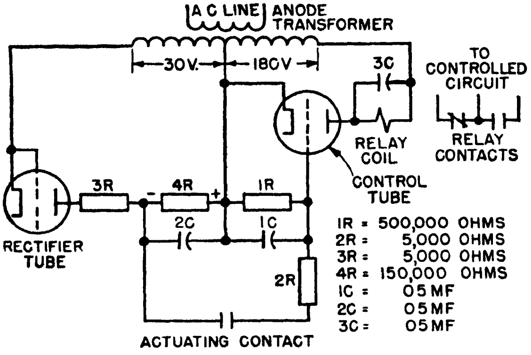


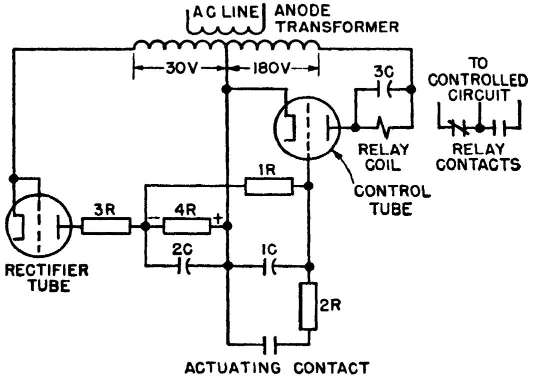
Fig. 168. Electronic relay.

Internal connections of the electronic relay are indicated in Fig. 169. For simplicity's sake, cathode heaters are omitted. The two triodes of the twin tube are shown as separate tubes, to make the circuit easier to understand.

With connections as in sketch *A*, the telephone relay is energized when the actuating contact is open, and the relay drops out when the actuating contact closes. The secondary winding of the anode transformer is tapped. Thirty volts are impressed on one of the triodes which is connected as a rectifier. A d-c voltage appears across resistor 4*R* and capacitor 2*C* with polarity as indicated. On the other triode, which acts as a control tube, 180 volts are impressed. With the actuating contact open, the grid of the control tube is at cathode potential. The control tube is conducting, and rectified half-wave d-c current, which is filtered by capacitor 3*C*, flows through the coil of the telephone relay.



A – CONNECTION FOR RELAY TO DROP OUT



B – CONNECTION FOR RELAY TO PICK UP

FIG. 169. Connections of electronic relay.

When the actuating contact closes, a negative bias voltage is applied to the grid of the control tube, which then ceases to conduct.

Consequently, the telephone relay drops out. When the actuating contact reopens again, the telephone relay does not pick up immediately, as capacitor 1*C* maintains the negative grid bias for a time. Capacitor 1*C* discharges through resistor 1*R* and introduces a time delay before the telephone relay picks up again. If the time interval, during which the actuating contact bounces open, is less than the inherent time delay of the electronic relay, the telephone relay does not chatter but stays dropped out.

In sketch *B* the function of the actuating contact is reversed. It is similar to sketch *A*, except that connections of resistor 1*R* and the actuating contact are changed. With the actuating contact open, a negative bias voltage is applied to the control tube grid, which does not conduct, and the telephone relay is dropped out. When the actuating contact closes, it connects the control tube grid to cathode potential. Consequently the control tube conducts current and the telephone relay picks up.

Electronic Timers[1,4]

In the electronic relay just described a time delay is obtained which is governed by the time required to discharge a capacitor through a resistor. This time delay is fixed, and no attempt is made to make the time delay either accurate or adjustable. With the same essential circuit components, namely, a 6C5 triode, a telephone

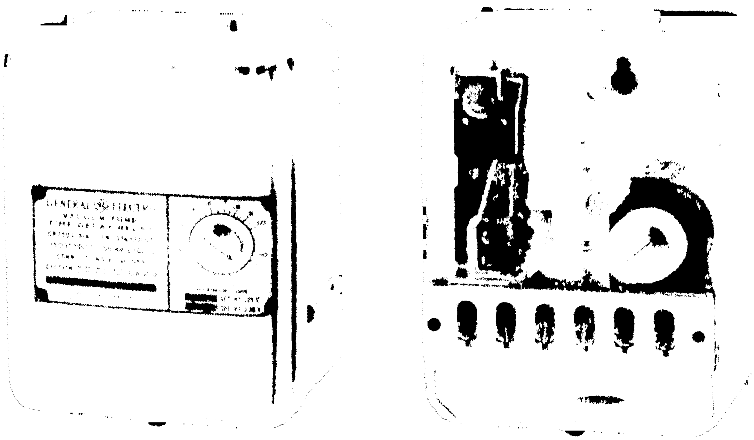

A *B*

FIG. 170. Electronic timer. *A*. General view. *B*. With cover removed.

relay, several resistors and capacitors, and an adjusting rheostat, *an electronic timer can be built which produces an accurate and adjustable time delay. A timer, assembled in its individual enclosing case, is shown in Fig. 170.* As compared with a mechanical timer or motor-driven time delay relay, it has the advantages that moving parts are absent and mechanical wear is eliminated.

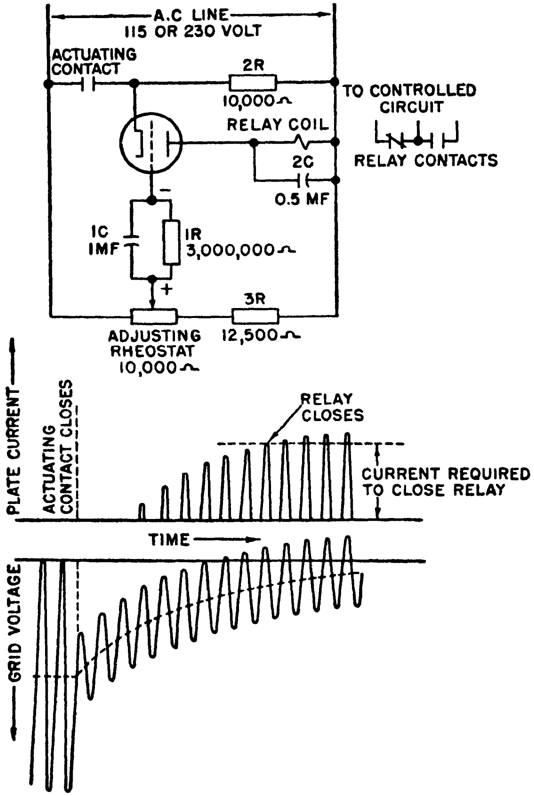


FIG. 171. Connections of electronic timer.

For internal connections and an explanation of the timing function, see Fig. 171. The timer is connected to either a 115-volt or 230-volt a-c system. The cathode heater of the tube is omitted for simplicity. With the actuating contact open, the timer is reset, and the telephone relay is dropped out, as the tube does not conduct current from cathode to anode. However, the grid and cathode of the tube form a rectifier, and current flows from the left side of the a-c line, through the adjusting rheostat, through resistor 1*R* and capacitor 1*C*, and through the tube and resistor 2*R* to the right side of the a-c line, the grid acting as an anode. This current charges capacitor 1*C*, until the capacitor voltage reaches the peak value of a-c voltage between the right side of the a-c line and the rheostat slider. With capacitor 1*C* fully charged, the grid voltage is always negative with respect to the right side of the a-c line so that no plate current passes the tube.

When the actuating contact is closed, this capacitor voltage plus an a-c voltage equal to the voltage from the left side of the a-c line to the slider of the rheostat is impressed on the grid. Since the cathode is now connected to the left side of the a-c line, the alternating component of the grid voltage is in phase with the cathode-anode voltage across the tube. Capacitor 1*C* discharges through resistor 1*R*, and the negative d-c voltage on the grid decays according to an exponential function, the time constant of which is determined by the product (1*R*) × (1*C*). In the lower sketch of Fig. 171, this decaying d-c voltage is indicated by a broken line. Over this d-c voltage the a-c grid voltage is superimposed so that the resultant grid voltage is represented by the solid line.

As long as the grid voltage is sufficiently negative, no plate current is passed by the tube. As the d-c component of the grid voltage decays, a point is reached at which the tube starts to conduct current, which consists of rectified pulses. Successive pulses increase in magnitude until the average current becomes large enough to pick up the telephone relay. Thus a definite time delay results between the closing of the actuating contact and the closing of the relay contact.

The time delay obtainable with the electronic timer is influenced by the selection of 1*C* and 1*R*, which determines the rate of decay of the d-c component of the grid voltage. With the values of 1*C* and 1*R* established, the actual time delay within the range of the relay can be adjusted by moving the slider of the rheostat. Moving the slider to the left increases the d-c component and decreases the a-c component of the grid voltage, thus increasing the time delay. Conversely, moving the rheostat slider to the right decreases the d-c component and increases the a-c component of the grid voltage, thus reducing the time delay.

Photoelectric Relays [1, 3, 6]

Photoelectric relays, as the name implies, make use of the phenomenon that light can affect the flow of current. The responsive element of a photoelectric relay is the phototube, which consists of a light-sensitive cathode and an anode, enclosed in an evacuated envelope. The light-sensitive cathode is usually a thin plate of silver on which a very fine film of sensitive material has been deposited by evaporation.

If voltage is applied to the anode and cathode in a dark room, no current flows through the phototube. If light strikes the cathode of the phototube, it emits electrons, and the tube passes current. The intensity of electron emission and the magnitude of current passing through the tube are approximately proportional to the intensity of the light striking the tube.

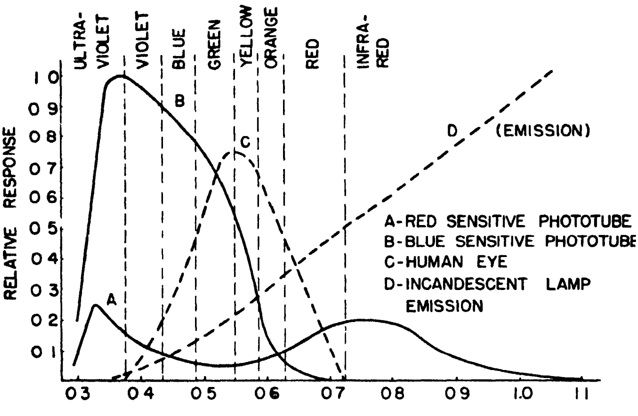


Fig. 172. Relative response of phototubes.

Photoelectric relays are often called "electric eyes," implying that phototubes "see" light and react to it like the human eye. There is some similarity in the response to light between the human eye and the phototube. Light is a mixture of oscillations of various wave lengths. There is a visible as well as an invisible spectrum. Within the visible spectrum, the human eye responds differently to different colors. If the response of the eye to light of different wave length is measured by an arbitrary standard, a certain pattern of response versus wave length is obtained. This pattern is plotted as curve *C* in Fig. 172.

Measuring the electron emission of a phototube, which is proportional to the current it passes, for light of different wave lengths, obtains a similar pattern of response versus wave length. Depending on the coating material of the cathode different response patterns are obtained. They are quite different from the response pattern of the human eye. Phototubes also have the property of responding to waves in the invisible spectrum.

Cesium oxide as a cathode coating material responds strongly to red and infrared rays. Response extends through the visible spectrum and reaches another peak in the ultraviolet range. The response pattern of a typical red-sensitive tube such as PJ23 is indicated by curve *A* in Fig. 172. The shape of that curve is quite different from the human eye curve *C*. The color range, which obtains maximum response of the human eye, obtains minimum response from the phototube and vice versa. This behavior of the phototube must be taken into consideration when it is used to "see" colored light.

A mixture of antimony and cesium oxide, properly processed, obtains a response pattern which is quite different. This cathode material obtains high response in the range of violet and blue, but low response in the red range, and no response at all in the infrared range. Curve *B* of Fig. 172 gives the response pattern of a blue-sensitive tube, such as GL441.

In connection with magnetic control, photoelectric relays are used principally as limit switches to indicate the position of an object in space. Photoelectric relays fill a definite need where it is difficult to use a mechanically operated limit switch. For instance, if it is desired to determine whether a piece of work has moved to a certain spot on a conveyor, at which point it is to be removed, a photoelectric relay can be used to "see" the piece of work and provide a control impulse which starts a deflector. Photoelectric relays are particularly valuable to determine the position of work inside furnaces. Roller hearth furnaces are a typical example. It is impossible to place limit switches inside a furnace because of the high temperature. Actuating mechanisms, which transmit mechanical motion from the inside of a furnace to a switch on the outside, are complicated and not practical at high temperatures. Photoelectric relays, however, can be used to "see" the work inside the furnace.

The customary arrangement is to use a photoelectric relay in conjunction with a light source. The light beam is trained on the phototube. When the object to be "seen" moves to the position at which a control impulse is desired, the light beam is intercepted and the phototube is darkened. Shown in Fig. 173 is a typical light source containing a low-voltage incandescent lamp, which is connected to the available power system through a step-down transformer. A standard automobile headlamp is used in the design shown. The mounting bracket permits adjusting the position of the

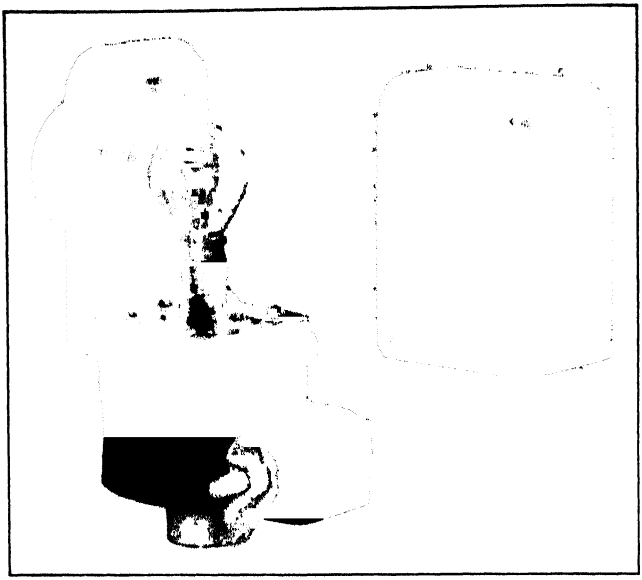
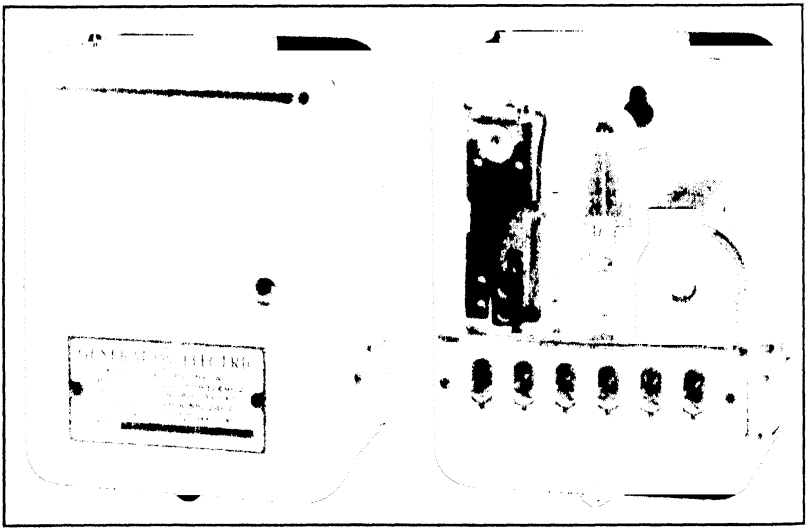


FIG. 173 Light source for photoelectric relays



A *B*

FIG. 174. Simple photoelectric relay with phototube included in relay box. *A*. General view. *B*. With cover removed.

lamp. A lens in front of the lamp gathers the emitted light and concentrates it into a well-defined beam.

In Fig. 172 curve *D* indicates the relative intensity of various wave lengths present in the light emitted by an incandescent lamp. The light beam contains a large amount of red and infrared rays. Thus red-sensitive phototubes are well suited for work in conjunction with incandescent light sources, as such tubes have a high degree of response in the red and infrared range.

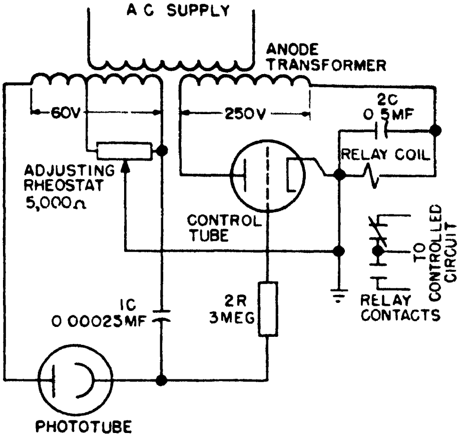


FIG. 175. Connections of photoelectric relay.

Figure 174 shows a simple photoelectric relay consisting of a phototube, a triode, a telephone relay and necessary transformer, resistors, and capacitors assembled in a sheet metal box. A slot in the cover permits the light beam to strike the phototube. Figure 175 is the elementary diagram of the relay. For an explanation of the circuit, assume that the phototube is dark so that no current passes through it. Since the cathode of the control tube is tied to the 60-volt winding of the anode transformer, the grid-cathode circuit acts as a rectifier and current flows through capacitor 1*C*, resistor 2*R*, the grid, the cathode, and back to the slider of the adjusting rheostat. This current charges capacitor 1*C* so that the grid of the control tube is always negative with respect to the cathode, thus preventing the control tube from conducting. The telephone relay is dropped out. When light strikes the phototube, it passes current during the positive half cycle because of the emission of electrons from its sensitive cathode. The phototube current reduces the negative charge of capacitor 1*C*, which was built up during preceding negative half cycles. As the light intensity and correspondingly the current through the phototube increase, the capacitor charge is reversed during the positive half cycle. This reversal applies a positive voltage to the grid of the control tube, which permits sufficient current to flow so that the telephone relay picks up. The amount of negative charge on $1C$, and thus the amount of light required to reverse the charge and obtain pick-up of the relay, can be varied by the adjusting rheostat. Resistor $2R$ protects the grid and prevents excessive grid current from flowing if light of high intensity strikes the phototube.

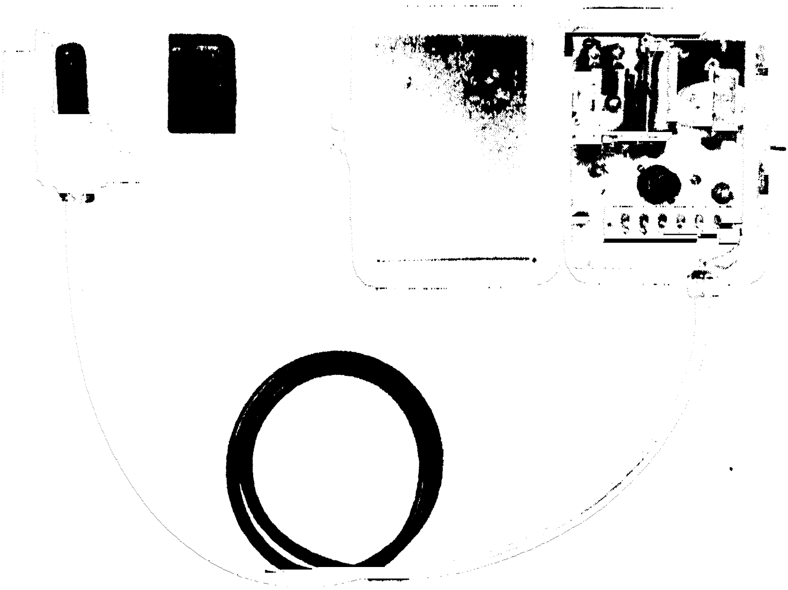


FIG. 176 Photoelectric relay with separate phototube holder.

The intensity of light which strikes the phototube is important for successful performance of the relay. The light source and the phototube must be lined up carefully so that the light beam is well directed on the tube. Dirt collecting on the lens of the light source or in front of the phototube impairs the response of the relay. Where accumulation of dirt cannot be avoided, it is well to lay out the control circuits in such a manner that the control will fail safe and not initiate a faulty and dangerous operation if the light beam is inadvertently intercepted by an accumulation of dirt.

In crowded quarters it may be found difficult to install a relay such as shown in Fig. 174 in a position where it can be lined up well with the light source. A relay with separate phototube holder is then used (see Fig. 176). The separate holder is much smaller than a complete relay and can be mounted easily in confined space. The phototube holder can be equipped with an optical system which permits focusing the light beam on the phototube, eliminating the effect of stray light, and increasing the intensity of the useful beam. When a separate phototube holder is used, the cable between phototube and relay must be of a shielded type and the shield must be grounded to prevent stray voltages from being picked up and applied to the grid, causing faulty operation The relay shown in Fig 176 uses the same circuit as given in Fig 175 except that a magnetic control relay has been added, which in turn is controlled by the telephone relay. This increases the contact capacity and permits the photoelectric relay to be used directly as a pilot device in control circuits requiring more power than can be handled by the telephone relay.

Fig. 177 Photoelectric relays used as limit switches on roller hearth furnace.

Shown in Fig 177 is a typical application of photoelectric relays as limit switches on a roller hearth furnace To the left and in front of the charging door is the relay, lined up with a light source to the right, which indicates that a charge has been placed on the charging table, ready to be moved into the furnace. When the charge intercepts the light beam, the relay provides the control impulse to open the door automatically. Some distance back, a second relay can be seen, the light beam of which is intercepted when the charge has moved a certain distance into the furnace. This interception provides another control impulse to close the door. Other relays are spaced at intervals along the furnace, controlling the progress of the charge through the furnace.

When photoelectric relays are applied to furnace work, consideration must be given to the temperature of the charge which the relay is expected to "see." At elevated temperatures the charge becomes incandescent and emits red and infrared rays to which red-sensitive phototubes respond. At 1450 F red-sensitive phototubes begin to react to the light emitted by the charge, but up to 1950 F it is possible to adjust the response of the relays so that a charge passing between light source and phototube causes the light beam to be intercepted. At higher temperatures, however, the charge emits so much red and infrared light that the phototube remains sensitized from the light of the charge.

One method of overcoming this difficulty is to reverse the action of the photoelectric relay and to omit the light source. A dark spot is provided in the furnace wall opposite the phototube, and as long as no charge passes before the tube, it is not sensitized. When a hot charge passes between the phototube and the dark spot, the tube becomes sensitized and conducts current. This arrangement, although simple and reliable, has the disadvantage that it does not fail safe in case of a phototube failure, and the hot charge may pass too far through the furnace. Above 1950 F blue-sensitive phototubes can be used in conjunction with a light source, as this type of tube does not respond to the rays emitted from the charge. A hot charge intercepts the light beam effectively and provides the required control signal. It is important to arrange control circuits so that phototube failure or burn-out of the light source prevents progress of the charge, avoiding a possible pile-up.

Pliotron Oscillators

Another electronic device which can be used as a limit switch to determine the position of a moving object in space is the pliotron oscillator. In Fig. 178 is a view of the oscillator, and Fig. 179 is the elementary diagram. The oscillator consists of a PJ8 pliotron triode which, together with a resistor and capacitors, is mounted in a case. In the back of the case are two wooden blocks, in each of which a coil is imbedded. The two coils are arranged so that they have a common magnetic axis, and so that the coils are coupled inductively. One coil is connected in the anode circuit, and the other coil is connected in the grid circuit of the pliotron tube.

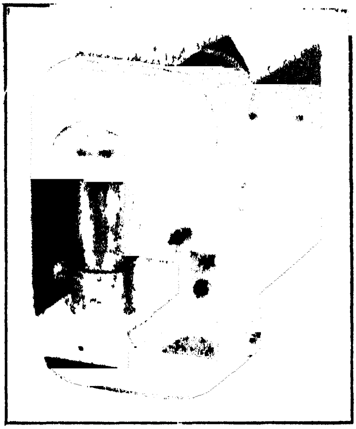


Fig. 178. Pliotron oscillator unit with cover omitted.

The tube is connected to a d-c voltage source, and the coil of a magnetic relay is connected in series with the anode. If the oscillator coils were short-circuited, the grid would be at cathode potential, and the tube would pass current commensurate with anode voltage. However, with the coils in the circuit, an oscillator is formed. A minute disturbance, such as a small switching surge, causes a transient voltage to appear across coil 2, and grid potential swings accordingly. A corresponding transient voltage, 180 degrees out of phase, appears across coil 1 in the anode circuit. Because of the inductive coupling between the coils, a 180-

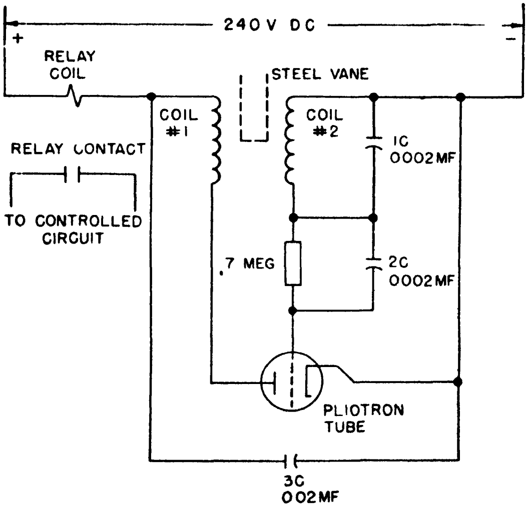


Fig. 179. Connections of pliotron oscillator.

degree out-of-phase signal is transmitted from coil 1 back into coil 2 that is, the reflected feed-back signal is in phase with the original signal which touched off the oscillation.

Capacitor 3C provides the return path for the current due to the oscillation, which continues at an amplitude and at a frequency at which the voltage gain of the feed-back circuit is exactly unity. While this high frequency oscillation exists only a small amount of direct current, approximately one milliampere, passes through the tube, which is insufficient for the relay to pick up. If a steel vane is inserted between the coils, their mutual inductance is changed, and the equilibrium condition of inductive coupling is disturbed. Consequently, the oscillation ceases, the grid assumes cathode potential, and the current through the tube jumps suddenly to a value between 15 and 20 milliamperes which causes the relay to pick up. Removing the vane restores the original condition of inductive coupling between coils, the high frequency oscillation starts again, the d-c current through the tube drops, and the relay drops out.

By coordinating a moving oscillator with a stationary vane or vice versa, the photron unit can be used as a limit switch, causing the relay to pick up when a moving body has reached a certain point in its travel. Pliotron oscillators have been used as leveling control units on elevators. By mounting pliotron units on the car and stationary vanes in the hatchway, control impulses can be obtained as a function of car position relative to a floor landing, which in turn are used to slow down and stop the car accurately and level with the landing.

Like photoelectric relays, pliotron oscillators have the advantage that they are not subject to mechanical wear, and they can be used at travel speeds which would preclude the use of mechanically operated limit switches. On the other hand, there are certain limitations which must be considered. The spacing between coils is a little less than one inch, and the moving element must be well guided to prevent the vane from hitting and damaging the coils. As the relay coil is energized (rather than de-energized) in the limit position, relay coil failure is not a safe failure, which makes the pliotron oscillator undesirable as an overtravel safety stop.

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CHAPTER 9

RESISTORS AND RHEOSTATS

Resistors are used in control equipments to introduce artificial voltage drops, to limit the voltage applied to a piece of apparatus, or to limit the current flowing in certain motor or control circuits. A resistor does not have the ability to store energy. All energy absorbed by the resistor is instantly transformed into heat. If the voltage applied to a resistor is changed, the current through the resistor changes instantly according to Ohm's law. Likewise, if the current through a resistor changes, the drop across the resistor changes instantly.

In designing a resistor for a controller, the following steps must be taken:

1. Determine the required resistance in ohms.
2. Determine the required current-carrying capacity.
3. Select the type of resistor best suited to the specific application.

The resistance to be used is governed by the effect it is desired to obtain in a motor or control circuit. The effect of resistance on motor characteristics is discussed in Chapters 2 and 3.

The resistance of a resistor unit depends on the specific resistance of material, its cross section, and the length of the current-carrying path. The current-carrying capacity is determined by the ability to dissipate the heat generated by the current flowing through it. NEMA specifies that the temperature rise of bare resistors shall not exceed 375 C, as measured by a thermocouple in contact with the resistive conductor, and the temperature rise of imbedded resistors shall not exceed 300 C as measured by a thermocouple in contact with the surface of the imbedding material. The temperature rise of issuing air shall not exceed 175 C, as measured by a mercury thermometer at a distance of one inch from the enclosure.

For industrial control work, the following types of resistors are commonly used:

1. Cast iron and punched steel grids.
2. Ribbon and wire wound units.

3. Enameled wire wound units.
4. Non-linear resistors, such as Thyrite.

Resistor Classifications

Resistors are subjected either to continuous or to intermittent duty. Resistors and rheostats for continuous duty are used primarily in generator or motor field circuits, or in control circuits. They are mostly wire wound units ranging in capacity from a few watts to a few kilowatts. Occasionally resistors are used for speed regulation of small and medium-sized motors as armature or slip ring resistance. Ribbon-wound units and grids are then used, which are also selected on the basis of continuous duty. Large motors are seldom used with speed-regulating resistors because of the large loss of power and the difficulty of dissipating the heat generated in the resistor.

Most resistors used for control applications are selected on an intermittent-duty basis. A starting resistor, for instance, carries current only during the starting cycle and is then short-circuited until the next start occurs. Likewise, resistors used for speed control of motors on intermittent drives carry current only during a portion of the total duty cycle of the motor. If a resistor is carrying current for only a short period of time, most of the heat generated is absorbed in the resistance material, and little heat is dissipated by radiation or convection while the resistor is connected to the power source. The mass of the resistor governs the amount of power it is able to absorb in a short time. If the resistor has to carry current for repeated time intervals, with off periods in between, the ability of the resistor to dissipate the heat and to cool during the off periods determines the temperature rise obtained during repeated duty cycles.

To select a resistor for a given controller, published data from the manufacturer are used which give the resistance in ohms and the current-carrying capacity which obtains a temperature rise within NEMA limitations. When calculating the ohms required, the designer should keep in mind that commercial resistors have a tolerance of plus or minus 10 per cent from the nominal resistance.

The published current-carrying capacity is usually the amount of current which would produce a 350 or 375 C temperature rise if the resistor were energized continuously. Sometimes the current-carrying capacity is given on a short-time basis, as the current which produces maximum temperature rise within a limited period of time. Although such data are of interest to compare various resistor designs, they do not form a satisfactory criterion for the application of resistors because they do not include the ability to dissipate heat during the off period. A satisfactory basis for application of resistors would be obtained if the current were known which, based on a definite time on and a definite time off, would produce the permissible temperature rise.

NEMA has established a standard resistor classification table based on two criteria. The first one governs current-carrying capacity. Several duty cycles, consisting of a number of seconds on out of a total time cycle, are standardized. The second criterion specifies the approximate current on the first controller step, expressed in percentage of motor full-load current. It determines the total resistance of the resistor in ohms. Table 11 gives the standard NEMA classifications. Each resistor classification consists of three digits. The first two digits designate the number of seconds on, out of a number of seconds representing the duration of the duty cycle. These two digits are significant for the resistor capacity. The third digit gives the current on the first controller step, which signifies the ohms. For example, resistors classified as 161, 162, 163, etc., have the same capacity but different ohms. Likewise, resistors classified as 141, 151, 161, etc., have the same ohms but different capacity.

TABLE 11

NEMA STANDARD RESISTOR CLASSIFICATIONS

Approx. Percentage Full-Load Current on First Point	30 Seconds on out of Each 15 Minutes	5 Seconds on out of Each 80 Seconds	10 Seconds on out of Each 80 Seconds	15 Seconds on out of Each 90 Seconds	15 Seconds on out of Each 60 Seconds	15 Seconds on out of Each 45 Seconds	15 Seconds on out of Each 30 Seconds	Continuous Duty
25	101	111	131	141	151	161	171	91
50	102	112	132	142	152	162	172	92
70	103	113	133	143	153	163	173	93
100	104	114	134	144	154	164	174	94
150	105	115	135	145	155	165	175	95
200 and over	106	116	136	146	156	166	176	96

To determine the NEMA classification rating of a given resistor, it is tested for temperature rise. NEMA has prescribed the following procedure. When a temperature test is made on a starting or intermittent-duty resistor without its motor, the resistor is connected to a voltage which obtains the initial inrush current specified. The steps are then cut out at equal intervals of time within the time-on period of the cycle specified. The voltage across the resistor is adjusted so that the current is maintained at 125 per cent of full-load current for those steps through which 125 per cent full-load current can flow. The specified cycle is repeated for one hour. This test does not correspond strictly to actual operating conditions which obtain while a motor is being started. During each step of the test, current is maintained constant, whereas under actual operating conditions the motor current changes on each step, depending upon the character of the load. Although the NEMA classifications are based on a simplified duty cycle which can easily be verified by a temperature test, the control designer has to use judgment when applying a resistor to a specific duty cycle load.

Resistor Application Data

As a guide to the selection of resistors for certain applications, NEMA has developed the following table of classifications. Operating experience has shown that the classifications listed are correct for average installations, but there are exceptions in special cases.

	Class
Blowers	
Centrifugal	133 93
Constant pressure	135-95
Brick Plants	
Augers	135
Conveyors	135
Dry pans	135
Pug mills	135
By-products Coke Plants	
Door machine	153
Leveler ram	153
Pusher bar	153
Rev. machines	153
Cement Mills	
Conveyors	135
Crushers	145
Elevators	135
Rotary dryers	145 95
Grinders, pulverizers	135
Kilns	135–95
Coal and Ore Bridges	
Bridge	153
Closing	162
Holding	162
Trolley	163
Coal Mines	
Car hauls	162
Conveyors	135 155
Coal Mines (*Continued*)	
Cutters	135
Crushers	145
Fans	134 93
Hoists—slope	172
—vertical	162
Jigs	135
Picking tables	135
Rotary car dumpers	153
Shaker screens	135
Compressors	
Constant speed	135
Varying speed—centrifugal	93
—plunger	95
Concrete Mixers	135
Cranes, General Purpose	
Hoist	153
Bridge—sleeve bearing	153
Bridge—roller bearing	152
Trolley—sleeve bearing	153
Trolley—roller bearing	152
Flour Mills	
Line shafting	135
Food Plants	
Butter churns	135
Dough mixers	135
Hoists	
Winch	153

	Class
Hoists (*Continued*)	
Mine slope	172
Mine vertical	162
Contractor hoists	152
Larry Cars	153
Lift Bridges	152
Machine Tools	
Bending rolls	163–164
Boring mills	135
Bull dozers	135
Drills	115
Gear cutters	115
Grinders	135
Hobbing machines	115
Lathes	115
Milling machines	115
Presses	135
Punches	135
Saws	115
Shapers	115
Metal Mining	
Ball, rod, tube mills	135
Car dumper, rotary	153
Converters, copper	154
Conveyors	135
Crushers	145
Tilting furnace	153
Paper Mills	
Beaters	135
Calenders	154 92
Pipe Working	
Cutting, threading	135
Expanding, flanging	135-95
Power Plants	
Clinker grinders	135
Coal crushers	135
Conveyors, belt	135
screw	135
Pulverized fuel feeders	135
Pulverizers, ball	135
centrifugal	134
Stokers	135–93
Pumps	
Centrifugal	135–93
Plunger	135–95
Rubber Mills	
Calenders	155
Crackers	135
Mixing mills	135

	Class
Rubber Mills (*Continued*)	
Washers	135
Steel Mills	
Accumulators	153
Casting machines, pig	153
Charging machines	153–163
Coiling machines	135
Converters, metal	154
Conveyors	135–155
Cranes, ladle	
Hoists	153–163
Bridge, trolley	
roller bearings	152–162
sleeve bearings	153–163
Crushers	145
Furnace doors	155
Gas valves	155
Gas washers	155
Hot metal mixers	163
Ingot buggy	153
Kickoff	153
Levelers	153
Manipulators	153–163
Pickling machines	153
Pilers, slab	153
Racks	153
Reelers	135
Saws	155
Screw downs	153–163
Shears	155
Shuffle bars	155
Side guards	153–163
Sizing rolls	155
Slab buggy	155
Soaking pit covers	155
Straighteners	153
Tables, approach	153
lift	153–163
roll	153
shear approach	153–163
transfer	153
main roll	153–163
Tilting furnace	153
Wire strander	153
Wood Working Plants	
Boring machines	115
Lathe	115
Mortiser	115

Wood Working Plants (*Continued*)	Class
Molder	115
Planers	115
Power trimmer	115
Power mitre	115
Sanders	115
Saws	115
Shapers	115
Shingle machine	115

Cast Grid Resistors

Resistance grids made of cast iron are among the oldest and most widely used types of resistors. Individual grids are cast in a shape approximating a square wave, with lugs in the end and in the middle to facilitate mounting. The resistance of each grid depends on its cross section, varying from 0.22 ohm to 0.01 ohm or less. Typical grids of large and small cross section are shown in Fig. 180.

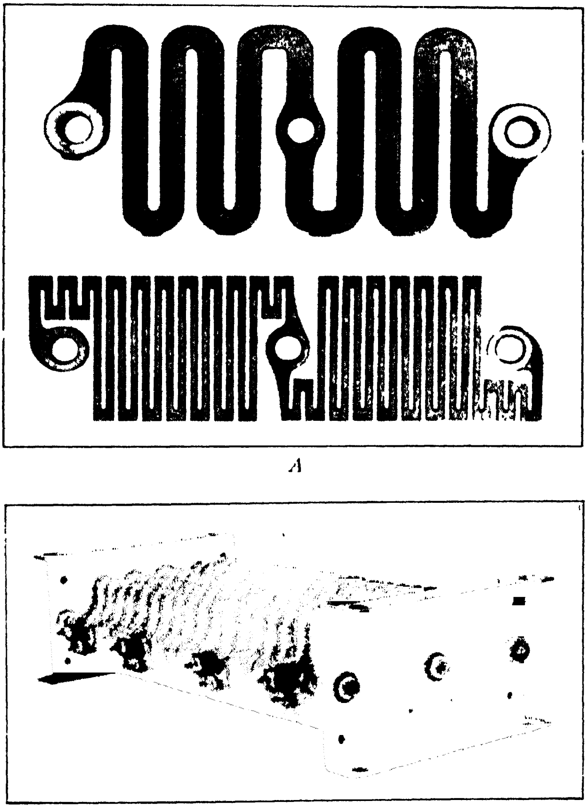


FIG. 180. Cast grid resistors. *A*. Individual grids *B*. Assembled box.

Grids are low in cost, but cast iron has low impact strength and grids of low cross section are likely to break when subjected to vibration or sharp blows. Although grids of large cross section are usually not subject to breakage, even in rough service, grids of small cross section should be avoided when resistors are exposed to jars and shocks, such as on cranes, chargers, or other moving machinery. As a general guide it may be said that cast grids having a continuous current rating of 50 amperes or less should be used judiciously. In selecting grid sizes, it should also be considered that grid breakage may occur during shipment from the factory to the point of installation, even though care is exercised in packing cast grid resistors for shipment.

Contrary to a widespread belief, cast grids are not easily damaged by corrosion. They will rust, and many cast grid resistors in actual installations present a not very clean appearance. However, the hard surface skin of the grids prevents rapid progress of corrosion. When cast grids are exposed to attack of particularly corrosive atmospheres, such as salt water atmosphere, corrosion resistance can be increased by alloying cast iron with a small amount of zinc, by zinc or cadmium plating, or by painting with aluminum paint.

Individual grids are stacked on insulated tie rods supported by sheet steel end frames. The whole assembly is called a box, as illustrated in Fig. 180. Grids can be connected either all in series or in series parallel connections. At points where it is desired to have contact between the ends of adjacent grids, soft copper washers are clamped between the lugs to insure low contact resistance. Mica washers are used between lugs where it is desired to insulate grids from each other. Box sizes are standardized to permit assembly of grids of various size in one box and to facilitate stacking of boxes. Many users prefer to have grids of only one size in any box, to simplify stocking of spare resistors. Such boxes are called *unit boxes*.

Cast grid resistors are used primarily when low resistance and high current-carrying capacity are required. Their principal field is starting and speed control of medium and large-size motors. For small motors, they are uneconomical. Cast grid resistors, when energized continuously, require a long time to heat up to ultimate temperature. This lag makes them particularly suited for applications where resistors are subjected to occasional overloads, and the ability to store a considerable amount of heat presents a definite advantage. On the other hand, cast grids take a long time to cool because of the low ratio of surface to mass, and it must be considered when establishing the rating of a resistor on a short-time duty cycle basis. In Fig. 181 the temperature rise versus time curves for various amounts of current are plotted for a typical cast grid. One hundred per cent current is the continuous current rating producing 350 C rise. The cooling curve is also shown.

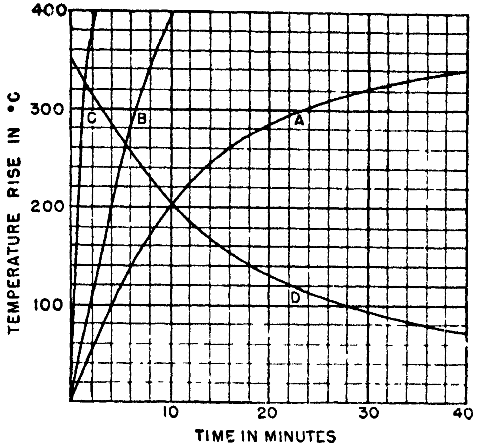


FIG. 181. Heating and cooling curves for a typical cast grid resistor. Curve *A*: Heating curve for 100 per cent current. Curve *B*: Heating curve for 115 per cent current. Curve *C*: Heating curve for 200 per cent current. Curve *D*: Cooling curve.

Punched Steel Grid Resistors

Punched steel grids are similar in construction and appearance to cast grids, except that the individual grids are not cast but punched out of sheet steel. The resistance of each grid depends on the gage of steel used and the grid width. Individual grids are assembled in boxes. Shown in Fig. 182 are an individual grid as well as a complete box.

As compared with cast grids, punched steel grids have the following advantages. Since the resistance material is more ductile than cast iron, the grids are less subject to damage by impact. Punched steel grids weigh less than cast grids of comparable rating, an advantage when resistors are mounted on moving machinery.

On the other hand, the cost of punched grids is higher than the cost of cast grids. As their mass is lower, punched grids reach their ultimate temperature faster than cast grids, and their ability to absorb short-time overloads is less. As they cool faster, they are about equivalent to cast grids, as far as their duty cycle ratings are concerned.

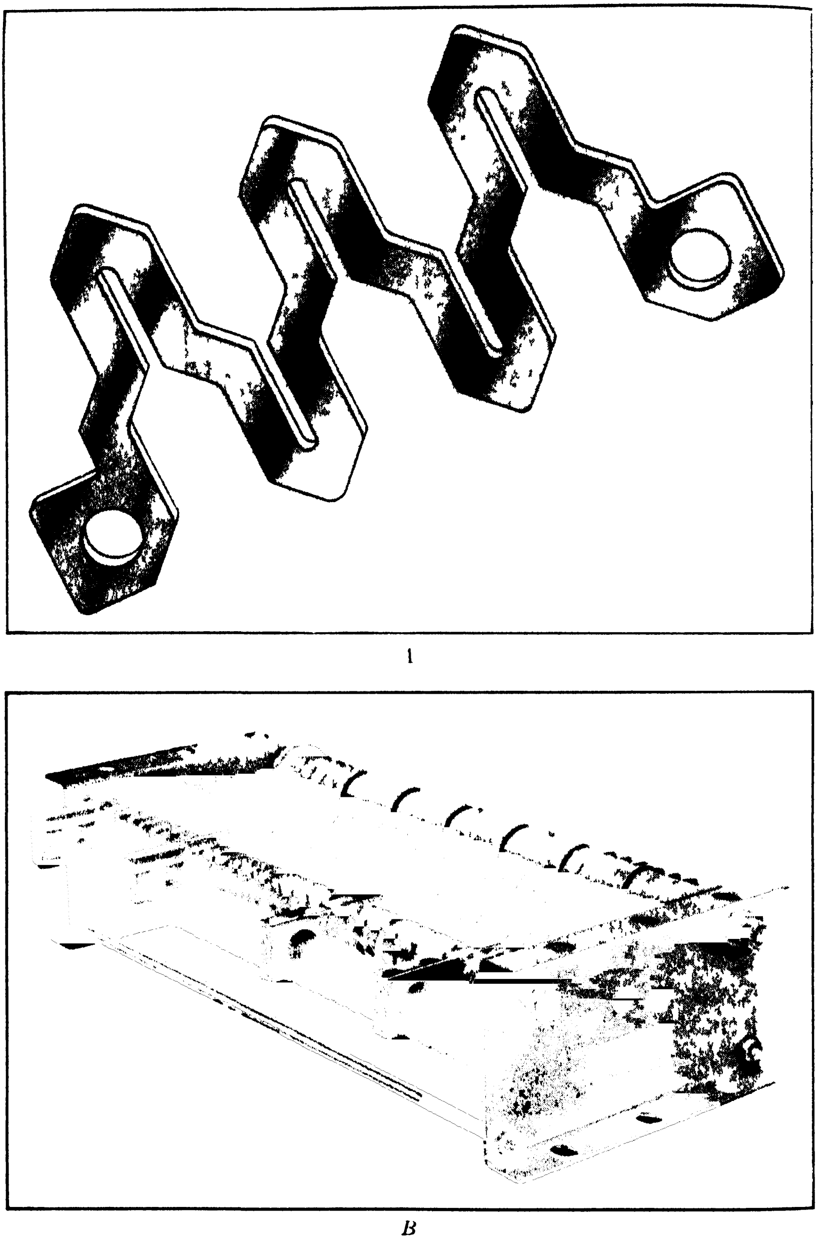


Fig. 182. Punched steel grid resistor. *A*. Individual grid. *B*. Assembled box. (Courtesy Post-Glover Electric Co.)

Ribbon and Wire Wound Resistors.

Ribbon and wire wound resistors consist of resistance materials having a high degree of ductility. Copper-nickel alloys, stainless iron, and nichrome are the most commonly used resistance materials. As such resistors are not easily damaged by vibration and impact, they are often referred to as *unbreakable*. One design which has found wide use in steel mills and on heavy duty equipments is illustrated in Fig. 183. A ribbon is edgewise wound over insulators assembled on a metal spacer, which gives the unit rigidity. Four or six units are assembled in a box. Connections between units consist

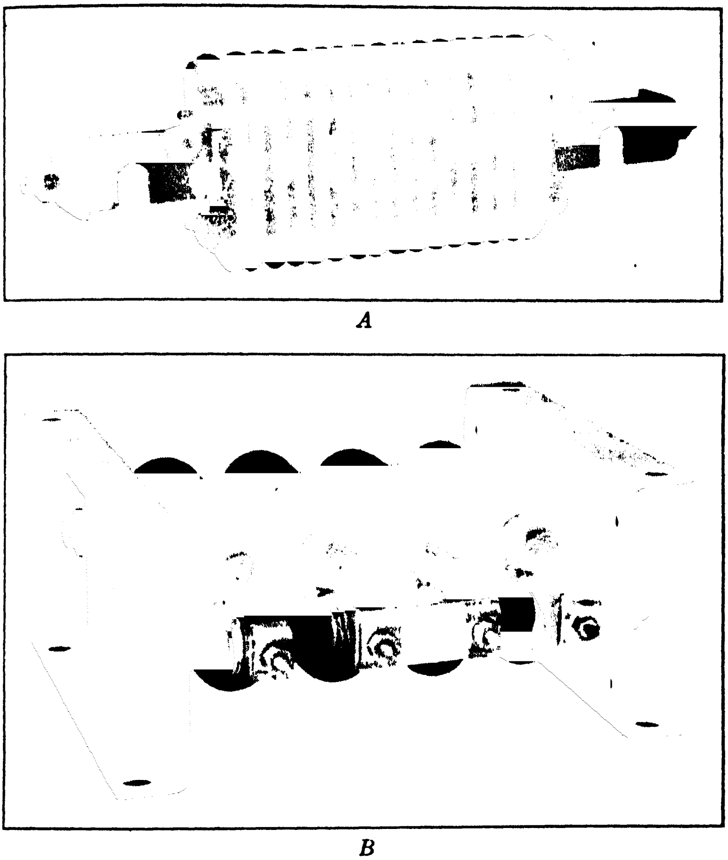
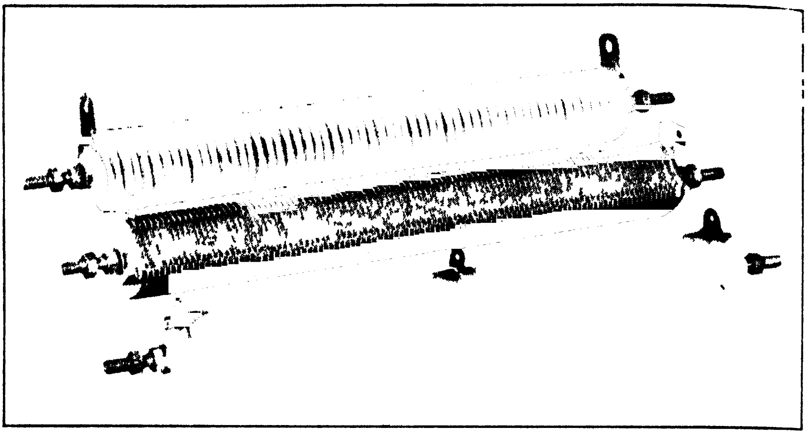
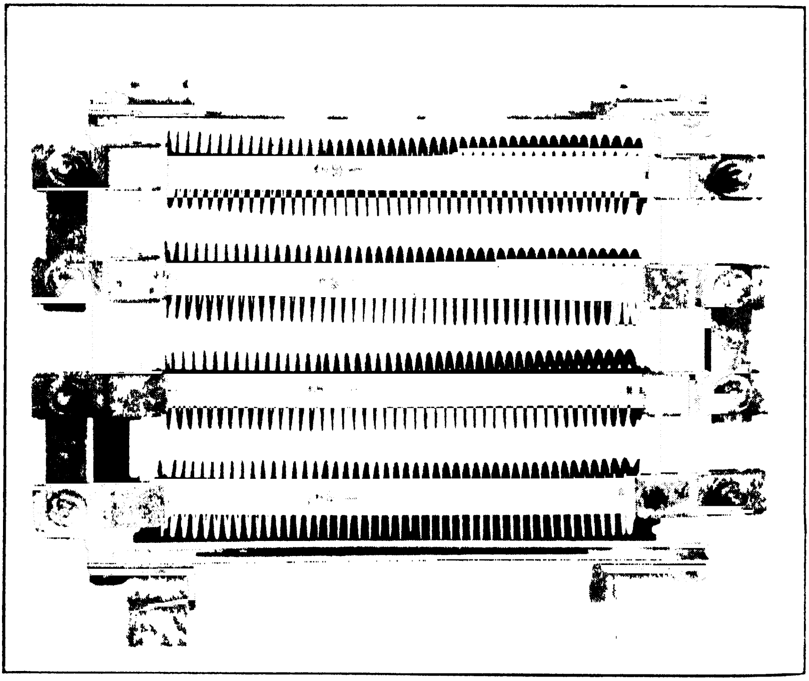


Fig. 183. Edgewise wound ribbon resistor. *A*. Individual unit. *B*. Assembled box.



A



B

FIG. 184. Edgewise and wire wound resistors *A* Individual units *B* Assembled box

of metal straps between the ends, which form the terminals. Units may be connected all in series or in series-parallel combinations.

Another design is shown in Fig. 184. The resistance material, in the form of ribbon or wire, is wound on a ceramic body. Several units can be combined in a box. Wire wound units have high resistance and low current-carrying capacity, which makes them useful for small motor and field circuits, where they are more economical than either grids or edgewise wound resistors.

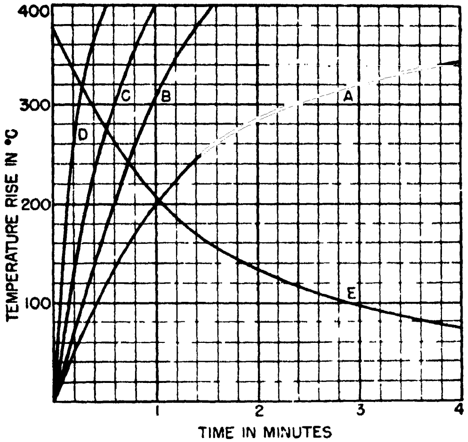


FIG. 185. Heating and cooling curves for a typical edgewise wound resistor. Curve *A*: Heating curve for 100 per cent current. Curve *B*: Heating curve for 125 per cent current. Curve *C*: Heating curve for 150 per cent current. Curve *D*: Heating curve for 200 per cent current. Curve *E*: Cooling curve.

Both ribbon and wire wound resistors are somewhat less flexible than grids, in that the resistance of each unit is fairly large. It is not possible, as in the case of grids, to obtain a fine adjustment by shifting connections from one unit to another. If it is expected that adjustments must be made at the installation, tap terminals should be provided. These are terminals which are brazed to the resistance material so that connections can be shifted at the installation by a fraction of a resistance unit. Taps can be seen in Fig. 184.

When ribbon wound resistors are used for large motors, it is necessary to connect several units in parallel to obtain the required current-carrying capacity. Caution must then be exercised because of the manufacturing tolerance of plus or minus 10 per cent in the resistance of individual units. Units connected in parallel may not divide the current evenly, which may result in overheating of some units if they are applied on the basis of their full rated current capacity. It is advisable to use them only up to about 90 per cent of their listed current rating.

As compared with cast grids, ribbon and wire wound resistors have less mass and less ability to store heat. They cannot absorb short-time overloads quite so readily. Much less time is required to reach ultimate temperature when rated current flows. The time during which the temperature limit is reached with currents higher than normal is greatly reduced On the other hand, the ratio of surface to volume is larger than for grids, and the spacing between units is larger Ribbon and wire wound resistors cool much faster than grids so that there is no appreciable difference between these types of resistors in their suitability for duty cycle applications. Heating and cooling curves for a typical edgewise wound resistor are plotted in Fig 185 A comparison with Fig 181 indicates that the shape of the curves is very similar in both cases, but the time scale of Fig 185 is only one tenth of that used in Fig 181.

Effect of Spacing

The current rating of a resistor is determined by the maximum temperature rise permitted by NEMA standards and the temperature of the issuing air. The rating of a resistor is influenced by the amount of air which may flow past it and carry away the heat generated by the flow of current The current-carrying capacity of a resistor is higher when the resistor is well ventilated; conversely, the current-carrying capacity is reduced when the flow of air is restricted.

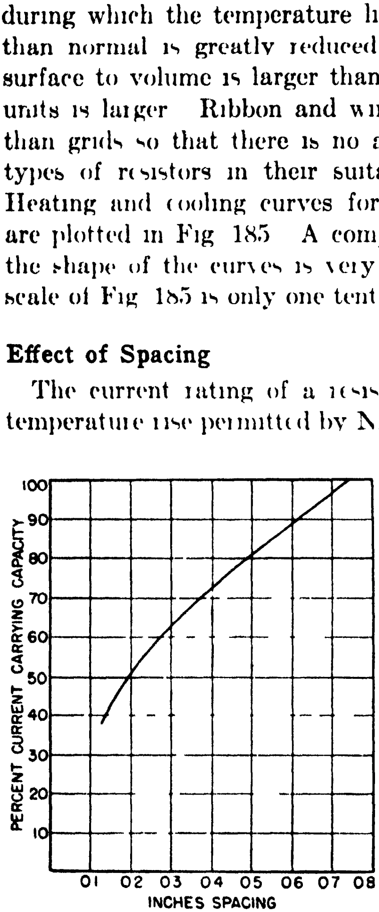


FIG. 186 Effect of grid spacing on current-carrying capacity

The current-carrying capacity of a resistor box depends on the spacing of the units or grids The closer the individual units are spaced, the more restricted is the flow of air Figure 186 shows the effect of grid spacing on the current-carrying capacity of punched steel grids. The current which obtains NEMA temperature limits at ¾ inch spacing between grids is called arbitrarily 100 per cent The curve indicates the extent to which the current-carrying capacity is reduced by closer grid spacing.

Many resistors consist of more than one box. To save floor space, it is common practice to stack boxes vertically. Care must be exercised to allow air to flow freely through the resistor stack. Air rising from hot resistor units produces a chimney effect, resulting in good air circulation. It is necessary to provide adequate spacing between boxes to permit sufficient cool air to enter the stack. Comparatively high cast grid and edgewise wound resistor boxes, as shown in Figs. 180 and 183, can be stacked six high without spacers and without derating. When stacked higher, the boxes must be spaced apart. Lower boxes, as shown in Fig. 184, must be derated or spaced apart when any number of boxes are assembled in a stack. Figure 187 shows the effect of number of boxes and spacing of boxes on current-carrying capacity of such resistors. Such curves must be determined by test, and they vary for different designs and makes of resistors. When a resistor requires high stacking, rating data should be obtained from the resistor manufacturer for the particular type of resistor used.

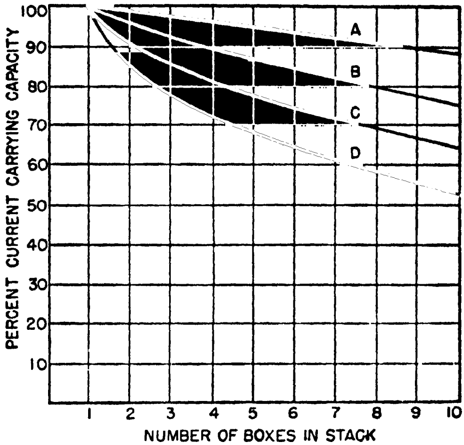


FIG. 187. Effect of spacing between boxes on current-carrying capacity of resistors as shown in Fig. 184. Curve *A*: 8½-inch spacers between boxes. Curve *B*: 4¼-inch spacers between boxes. Curve *C*: 2-inch spacers between boxes. Curve *D*: No spacers between boxes.

Effect of Altitude

When resistors are installed at high altitudes, the rarefied air is less efficient as a cooling medium than at sea level. Up to 6000 feet the effect of altitude is neglected. For installation at altitudes between 6000 and 15,000 feet, NEMA standards prescribe the following procedure for derating resistors. Continuous-duty resistors are derated to 75 per cent of their normal voltage rating. Intermittent- and starting-duty resistors are applied on a duty cycle selected on the basis of the next higher "time-on" classification (see Table 11).

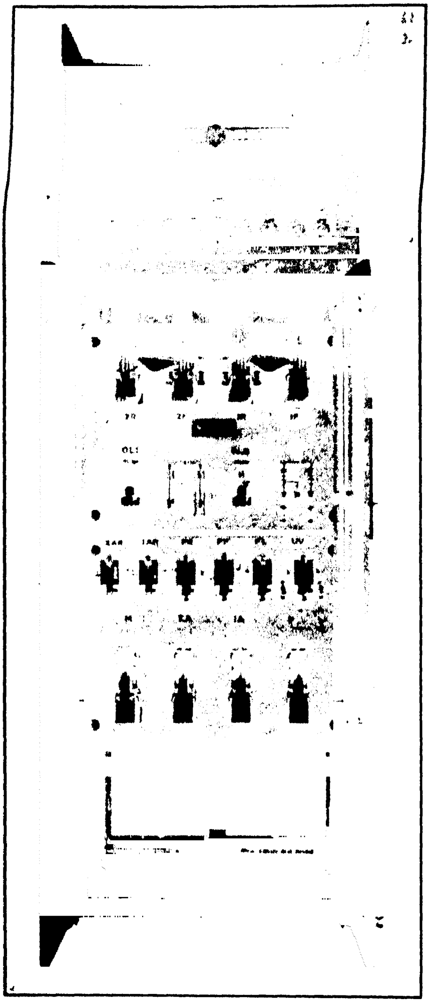


FIG. 188. Enclosed resistor on top of an enclosed panel

Enclosed Resistors

Resistors are sometimes enclosed to protect them against accumulation of dirt or against damage by falling objects. On starters requiring comparatively small resistors, it is often convenient to mount the resistor in the back of the panel, making it unnecessary to mount and wire the resistor at the installation. When such panels are enclosed, the resistor is inside the enclosure, and precautions must be taken to avoid overheating of the resistor or the panel.

When a resistor is mounted in a tight enclosure, which is sometimes necessary as protection against dust or weather, the heat generated in the resistor is dissipated only by radiation and convection from the surface of the enclosure. To determine whether an enclosure is suitable for a given resistor, the loss in the resistor in watts and the total cooling area of the enclosure in square inches are calculated. Assuming that the temperature rise of the air inside the case is to be limited to 200 C, to keep the temperature of the issuing air below 175 C, the enclosing case can dissipate between 1 and 2

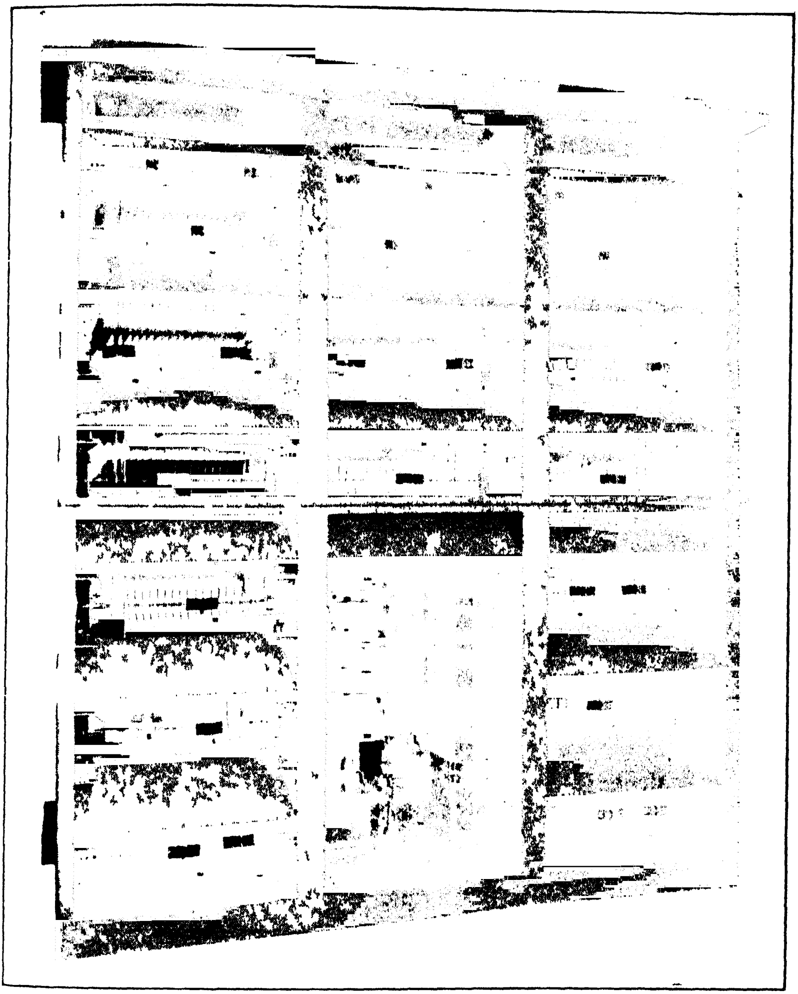


Fig 189 Enclosed forced ventilated resistor with back covers removed

watts per square inch of cooling surface The higher the case, the greater the difference in temperature existing between the top and the bottom Thus the higher the case, the lower the watts per square inch dissipation factor that should be used

If a resistor is mounted behind a panel enclosed in a tight case, it is necessary to limit the temperature in the front of the panel to avoid overheating of panel devices. To determine the watts which can be dissipated by the enclosure, the panel should not be considered *as dissipating heat. The heat-dissipating area consists of* the back, the top, and that part of the sides of the enclosure located back of the panel. To limit the temperature rise in front of the panel to 35 C, a dissipation factor of 0.4 to 0.5 watt per square inch cooling surface should be used. The higher the case, the lower the dissipation factor.

Resistor enclosures should be ventilated, if at all possible. Providing side openings near the bottom and near the top or leaving the top off altogether gives a good chimney effect. The best conditions are obtained when there are openings in both the top and the bottom. With ample ventilating openings, the resistor need not be derated. Under favorable conditions, a ventilated enclosed resistor may run cooler than an open resistor operating under the same service conditions. Figure 188 shows an enclosed resistor mounted on top of an enclosed control panel. The top of the resistor enclosure is open, and ventilating openings are cut in the front and back sheets.

Still better cooling is obtained with forced ventilation by a fan or blower. Resistors can then be used for currents considerably higher than their normal rating. The amount of power that can be dissipated depends on the amount of cooling air flow used. Uniform flow of air through all resistor sections must be insured. Figure 189 is the rear view of an enclosed forced ventilated resistor. The back covers are removed to show the arrangement of resistor boxes and baffles which distribute the flow of air.

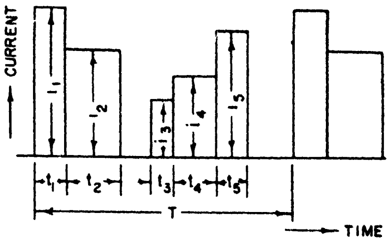
Duty Cycle Rating of Resistors

When a resistor is subjected to a definite short-time duty cycle, which is repeated indefinitely, the equivalent rms current can be calculated. The rms (root mean square) current is the continuous current which would produce the same heating as the actual current. In Fig. 190, i_1, i_2, i_3, etc., are the currents flowing during time intervals t_1, t_2, t_3, etc. With T being the total duration of a cycle, rms current I_{rms} is determined as follows:

$$I_{\text{rms}} = \sqrt{\frac{i_1{}^2t_1 + i_2{}^2t_2 + \cdots i_n{}^2t_n}{T}} \tag{65}$$

A resistor can then be selected having a continuous current rating equal to or larger than the rms current, I_{rms}.

This method of determining resistor rating is permissible as long as the cycle is short as compared with the thermal time constant of the resistor and the off periods are a small portion of the total cycle. If the off period is long as compared with the on period, it is necessary to consult test data on existing resistor designs, as the rate of heating and cooling and the ability of the resistor to absorb overloads of short duration play an important role. If a duty cycle consists of a short current peak followed by a long off period, the calculated rms current may be so low that a resistor selected for that current rating overheats during the current peak.



$$I_{RMS} = \sqrt{\frac{i_1^2 t_1 + i_2^2 t_2 + i_3^2 t_3 + i_4^2 t_4 + i_5^2 t_5}{T}}$$

FIG. 190. Determining rms current from duty cycle diagram.

In Fig. 191 a curve is plotted which gives the current-carrying capacity of a cast grid resistor in percentage of its continuous current rating when subjected to short duty cycles. The abscissa is the relative time on, that is, that portion of the total duty cycle during which the resistor carries current. On the time scale the points are marked which correspond to standard NEMA duty cycles. Although

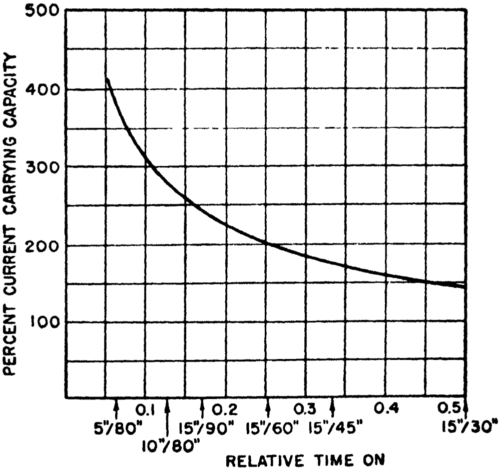


FIG. 191. Current-carrying capacity of cast grid resistors on short duty cycles.

the curve shown applies to a particular resistor, equivalent curves can be drawn from test data for other resistors which are of similar shape, although the actual current values differ somewhat between resistor types.

Enameled Resistors

Small resistors, which are used in control circuits, are mostly wire wound units. The resistance wire is wound on a ceramic tube. The whole unit is then dipped in vitreous enamel and fired. This vitrifies the enamel and gives the unit a hard glazed surface. The enamel serves to hold the resistance wire in place and to protect it against corrosion and mechanical injury in handling.

Enameled resistor units are available with resistance of a fraction of an ohm up to several thousand ohms. In size they range from small units rated a few watts up to about 150 watts. Figure 192 illustrates the variety of sizes and shapes that can be obtained. Taps may be provided for adjustment or a strip of wire may be left bare of enamel to permit adjustment by a sliding contact. Different terminals and mounting feet can be attached to the resistor tubes, such as ferrules or screw bases. As the ceramic tubes can be broken easily by careless handling, dropping of tools, etc., enamaled resistors are often protected by a sheet metal cage if they are mounted on large control panels. Such a cage type unit can be seen near the center of Fig. 192.

Rheostats

A rheostat is a resistor provided with means for varying its resistance readily. Rheostats are used principally in field circuits of motors or generators for the control of speed or voltage or in control circuits. Numerous styles and sizes are available, depending on the total resistance required and their current rating. The size of a rheostat depends on the energy which it must dissipate. It is determined by the characteristics of the machine with which it is used and the required speed or voltage variations.

Once the amount of resistance required has been ascertained, the current can be calculated which is obtained with all resistance inserted (minimum current) and with all resistance cut out (maximum current). A convenient way of rating rheostats is by *summation watts*, which is the resistance in ohms, multiplied by the minimum current, multiplied by the maximum current.

Many forms of rheostats are built. Small rheostats, as used primarily in control circuits, consist of a ceramic body on which the

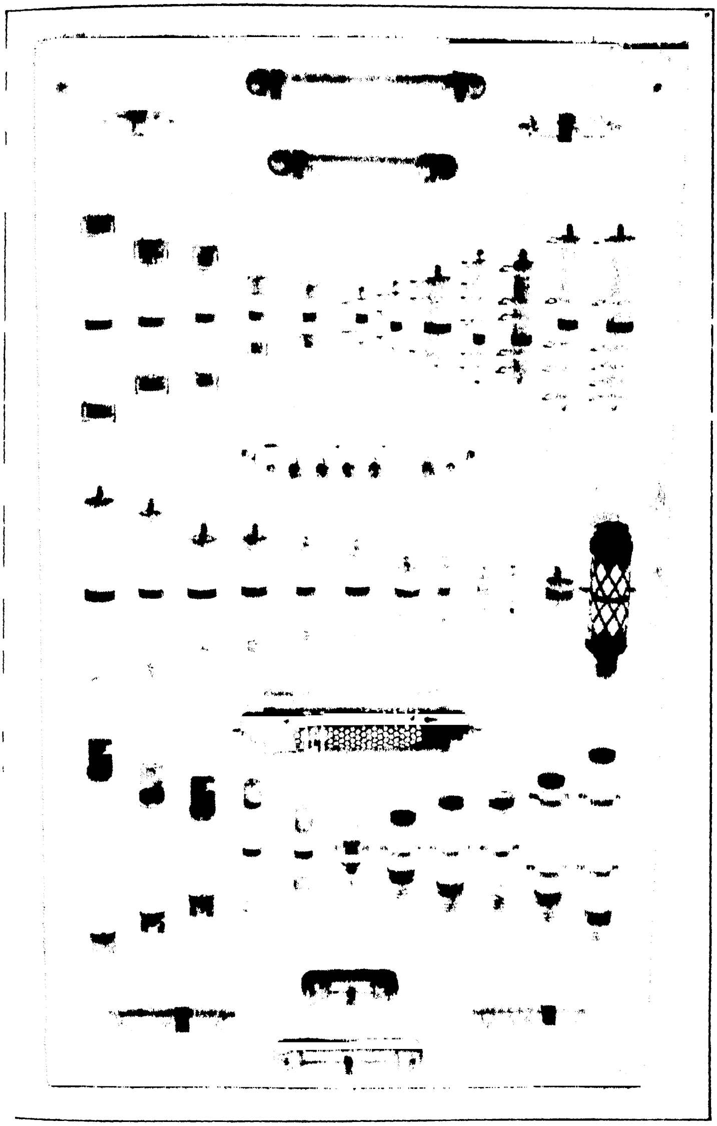


FIG 192 Vitreous enameled resistor units

bare resistance wire is wound. A brush, connected to a rotating arm, slides over the wire and permits adjustment of resistance. Such rheostats have given excellent service when properly applied, but there are two limitations. As the brush slides on the wire, there is a limit to the amount of current that can be commutated by the brush. With high rheostat resistance, the cross section of the wire becomes very small, and the brush may wear through the wire if too fine a wire is used on rheostats that are frequently operated.

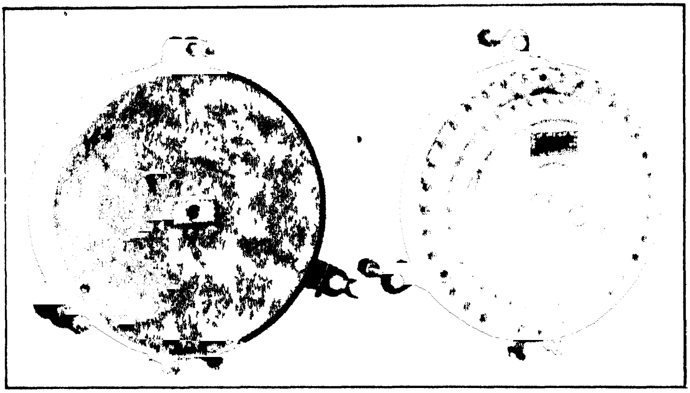


Fig. 193 Plate type rheostats

Rheostats for medium and large-size motor fields are built as a face plate with buttons or segments, to which resistor elements are connected and over which the brush slides. Higher currents can be commutated, and wear occurs on the heavier contact pieces rather than on the resistance material. So-called *plate rheostats* have a metallic face plate, which is filled with ceramic material into which the resistance wire is imbedded. The resulting sturdy construction lessens the danger of breakage. Such a rheostat is shown in Fig. 193. It may be mounted either on the front of a control panel or in the back of a panel with the operating handwheel protruding through the front of the panel. Still larger rheostats are built as a panel with one or several rows of contact buttons, over which a contact arm sweeps. The resistance elements are built into a separate assembly.

Large rheostats may become rather bulky and hard to operate by hand. Motor-operated rheostats use a small pilot motor to turn the rheostat contact arm, permitting remote operation of the rheostat by means of a small pilot device. Manual as well as automatic operation is possible. Figure 194 illustrates a rheostat consisting of a frame in which the resistance elements are mounted. The panel with the buttons is fastened to the front of the frame. A small pilot motor turns the contact arm through suitable gearing. Limit switches open at the ends of travel in both directions to prevent overdriving of the contact arm. For emergency, a handwheel is provided to turn the rheostat arm by hand.

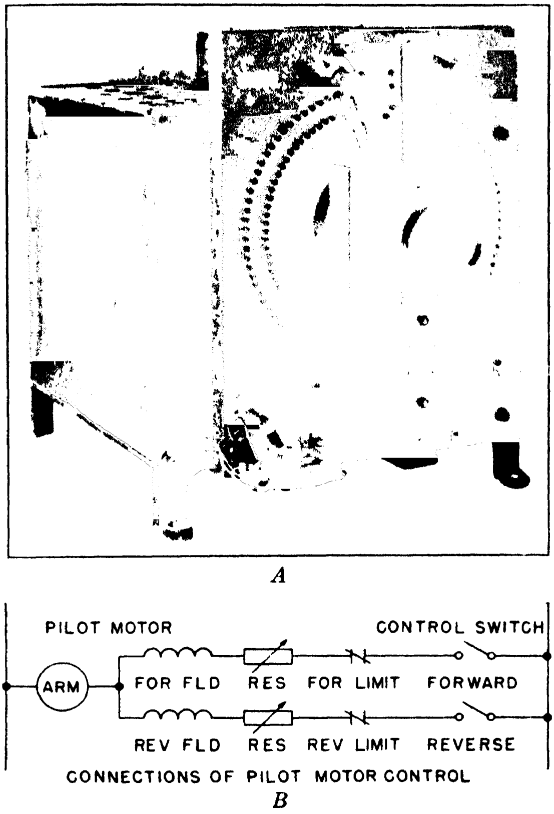


Fig. 194. Motor-operated rheostat. *A* General view. *B*. Connections of pilot motor control.

Pilot motors are either split-field d-c series motors or a-c universal motors. The lower part of Fig. 194 is a diagram of a simple manual control for a rheostat pilot motor. Closing the forward or reverse control switch energizes the pilot motor through either field, thus selecting the direction of rotation. Adjustable resistors in series with both fields permit adjusting the speed of rheostat travel independently in both directions. Limit switch contacts cut off the motor at the ends of travel.

To select a rheostat for field control of a motor, it is necessary to know the cold resistance of the shunt field and the field current at maximum speed. Cold resistance of the field is used to make certain that maximum speed can be reached before the motor has warmed up. The total resistance required in the rheostat is equal to line voltage divided by weakened field current, minus field resistance. When dividing the total resistance into steps, it is most desirable to calculate each rheostat point so as to obtain equal speed increments per step. Equal ohms per division obtain sufficiently uniform speed increments per step for most practical purposes. If a high degree of uniformity is desired, resistance steps are calculated from the motor speed versus field current curve, obtained from the motor designer.

However, when a rheostat is laid out with equal ohms per step, the watts dissipation per step at the high current end is considerably larger than at the low current end, resulting in an inefficient utilization of the resistance material. Best utilization of resistance material would be obtained if equal watts were dissipated per step. This in turn would obtain very unequal speed increments per step. To arrive at a practical layout of a motor field rheostat, a compromise must be made between most desirable speed variation and most economical layout of resistance per step. Experience has shown that a 6-to-1 taper between the low-current ends and the high-current ends obtains satisfactory speed control for average installations. By a 6-to-1 taper is meant that the last step of the rheostat has six times the resistance of the first step.

Rheostats for the control of generator or exciter fields are laid out along similar lines. An ideal generator rheostat would obtain equal voltage change per division. When working on the straight-line portion of the generator saturation curve, equal resistance steps correspond to equal voltage steps. As saturation sets in, the resistance per step must be increased to conform to the shape of the saturation curve. When definite requirements of equal voltage change per step are to be met, the no-load and full-load saturation curves must be considered over the full voltage range.

Field rheostats for self-excited generators are selected so that the no-load voltage can be reduced to one half rated voltage. For generators with separately excited shunt field, the rheostat should have sufficient resistance to reduce the no-load voltage to 85 per cent of rated voltage.

Liquid Rheostats

Resistors and rheostats, using a liquid saline solution as resistance material, have been widely used in Europe because of their comparatively low cost. They have not become popular in the United States, as their maintenance is high. However, in certain special cases they have been used successfully in this country, especially as slip regulators for large wound rotor induction motors driving flywheel motor generator sets for adjustable-voltage systems, particularly for steel mill drives and mine hoists.

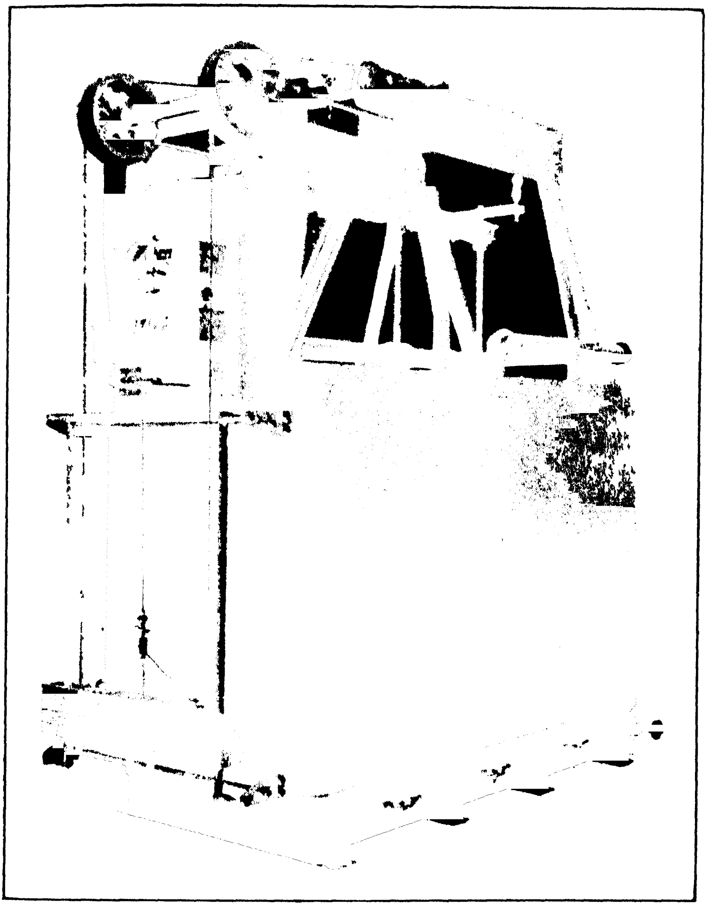


Fig. 195. Liquid slip regulator.

The purpose of a flywheel set is to equalize sudden variations in load. During peak load demands the flywheel is discharged. While the load is below average, the flywheel is charged again. If power *is to be taken from the line at a uniform average rate, the slip of the* induction motor must be varied over a certain range determined by Wk^2 of the flywheel and the load in wattseconds which the flywheel is rated to deliver. The variation in slip must be closely controlled as a function of load. Liquid slip regulators are used to vary the secondary resistance in a practically infinite number of steps.

Slip regulators are large pieces of apparatus. A typical design for a 4000-hp motor is illustrated in Fig. 195. Dimensions are 11 feet 6 inches high, 10 feet 3 inches wide, 4 feet 3 inches deep. A steel tank containing the saline solution is subdivided into three compartments, corresponding to the three rotor phases. Stationary electrodes in the bottom are connected to the motor secondary terminals. Movable electrodes, suspended from a cross bar, form the wye point. The distance between stationary and movable electrodes is a measure of resistance per phase. The actual resistance in ohms is determined by the physical dimensions and the concentration of the solution. The movable electrodes are counterweighted. A torque motor, actuated by the current in the induction motor stator circuit, raises or lowers the electrodes to maintain constant line current.

Because of the large amount of heat generated by the I^2R losses in the regulator, the solution must be cooled. It can be done by building cooling coils into the tank or by circulating the solution through an external cooler.

Thyrite Resistors [4, 5]

Thyrite is a non-linear resistance material in which the current varies as a power of the applied voltage. It has found important applications as a protector to limit voltage surges, as a stabilizer in circuits supplied by rectifiers, as a potentiometer with voltage division nearly independent of load current, or for the control of voltage selective circuits. In the industrial control field, Thyrite is used primarily as a protector, to reduce voltage surges when inductive circuits are interrupted.

Thyrite is made by pressing silicon carbide with a suitable ceramic binder at high pressure, followed by a firing operation at approximately 1200 C. Electrical contact is made to Thyrite through a metal coating sprayed on the surfaces. Shown in Fig. 196 are discharge resistors, made of Thyrite, in various sizes. Small units are mounted on brackets, larger disks are assembled on a bolt, which mounts in a hole in the control panel.

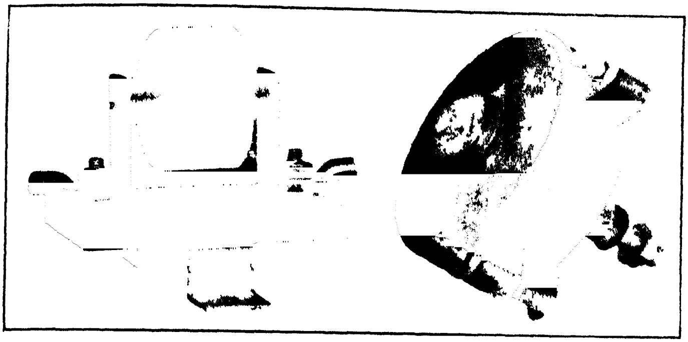


FIG. 196. Thyrite discharge resistors.

The volt-ampere characteristic of a Thyrite resistor can be expressed as follows:

$$i = \left(\frac{e}{c}\right)^n = Ke^n \qquad (66)$$

where i = instantaneous a-c or d-c current passed by Thyrite,
e = instantaneous a-c or d-c voltage applied to Thyrite,
c = a constant (volts at one ampere),
K = a constant (amperes at one volt),
n = an exponent.

Constants c and K depend on the resistivity and the dimensions of the particular resistor under consideration. Exponent n depends upon

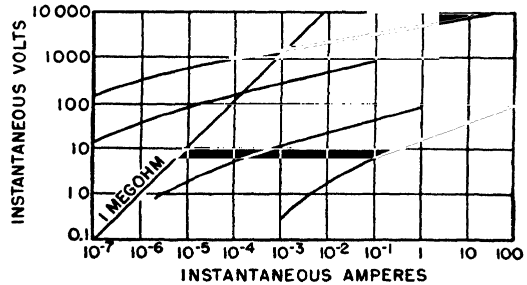


FIG. 197. Typical volt-ampere characteristics of Thyrite resistors.

various factors in the manufacturing process, and it varies between 3.7 and 7. The volt-ampere characteristics of typical Thyrite units are shown in Fig. 197, in comparison with a one megohm linear resistor. The effect of exponent n can be explained by the following example. When the voltage across a linear resistor is doubled, the current through it increases by a ratio of 2. Doubling the voltage applied to a Thyrite resistor increases the current by a ratio of 11 if $n = 3.5$ and by a ratio of 128 if $n = 7$.

When a Thyrite resistor is connected in parallel with a motor or generator shunt field, a negligible amount of current flows when normal voltage is applied to the field. When the field circuit is interrupted, the voltage across the field terminals and the Thyrite resistor rises rapidly. If the Thyrite resistor is selected so that at four times normal voltage normal field current can flow through the Thyrite, the voltage rise across the field terminals is limited to four times normal voltage. In a 250-volt field this would correspond to a maximum of 1000 volts, which is considered a safe value for standard d-c machines.

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CHAPTER 10

CONSTRUCTION OF CONTROL PANELS

To make up a magnetic controller, individual contactors, relays, switches, circuit breakers, instruments, and sundry accessories are assembled and interconnected on a control panel. On large equipments, control for a multiplicity of motors may be combined on one panel. Interconnections between devices are less expensive when made on a panel in the factory than when run through conduits at the installation. Better testing facilities are available in a factory than at a construction site, and complicated interconnecting wiring can be tested in less time and at less expense when it is on a panel. The trend is to combine as many devices as possible on panels rather than to purchase individual devices and assemble them into an integrated controller at the installation.

According to the method in which they are mounted, panels can be divided into the following types.

Wall mounted (small panels).
Built-in (special, particularly for machine tools).
Floor mounted (large panels).

Depending on the manner in which control panels are constructed, the following classification can be made:

Open panels.
Frameworks.
Enclosed panels.
Control desks.
Packaged controllers.

Generally speaking, any panel consists of a base or bases, on which individual devices are mounted, and structural supporting members. Before various methods of constructing panels are described it is well to discuss general features common to all panels.

Choice of Base Material

Materials used as bases on industrial control panels are steel, slate, and ebony asbestos compound.

Cold-rolled steel sheets $\frac{1}{16}$, $\frac{3}{32}$, and $\frac{1}{8}$ inch thick are used principally as base material for manually operated pilot devices, such as push buttons and control switches. Steel panels can be grounded easily and thus all structural device parts, which do not carry current, and operating handles are at ground potential. This grounding insures *safety to the operator* since any breakdown of the insulation between current-carrying parts and operating handles results in a fault to ground, and no parts that must be touched by the operator can be above ground potential. Figure 198 is a typical floor-mounted steel panel containing a number of control switches and indicating lights.

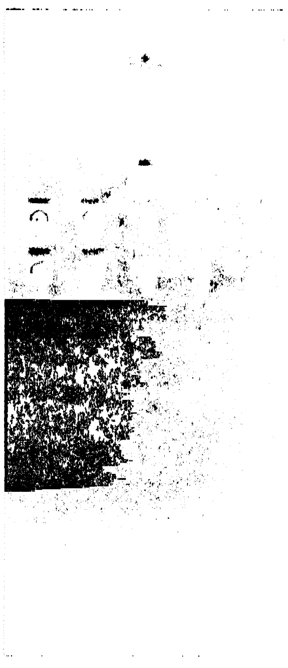

Fig. 198. Open steel panel containing control switches and indicating lights.

There is a growing trend toward building small and medium-size contactors and relays as self-contained devices, suitable for mounting on steel. Steel is being used more and more as a base material for magnetic control panels, its selection being governed largely by manufacturing considerations. Steel bases can be machined easily. Round and irregular holes can be punched, and machine tools are available to punch sheet steel economically. Steel as a base material has the advantage of not being damaged by shock or vibration. In designing a steel panel, care must be taken to insure sufficient rigidity. On large panels, the edges are bent in and welded at the corners so that the base is pan shaped. If necessary, reinforcing ribs are welded to the back to prevent the weight of devices from buckling the base.

Slate and ebony asbestos compound are insulating materials, and current-carrying parts can be brought in direct contact with the base material. Many magnetic devices are designed so that current-carrying studs are used as mounting studs, and the base material provides the insulation between devices and to ground. When devices are laid out on a panel, the minimum distances between current-carrying parts of opposite potential and to grounded panel supports must conform to Table 17 (page 398).

Slate is a natural rock product, obtained by quarry mining. The quarried slate is split to the desired thickness and cut to size at the mine. Natural slate may include metallic veins, which form conducting paths. When slate is selected for panel bases, any slate with metallic veins imbedded in it must be eliminated.

Ebony asbestos compound is a synthetic material, including asbestos fiber. It is made by a hot-pressure molding process, and it is furnished by the manufacturer as sheets with a thickness up to 2 inches and in sizes up to 96 inches by 48 inches. Because it is a synthetic material, the uniformity of its composition is easily controlled and metallic inclusions are absent.

A comparison of the physical properties of slate and ebony asbestos is given in Table 12. There is not a great deal of difference in properties between the two base materials, and both are used extensively for industrial control panls. The following considerations may influence the choice between base materials for a specific application:

TABLE 12

COMPARISON OF PHYSICAL PROPERTIES OF SLATE AND EBONY ASBESTOS COMPOUND

	Base Material	
Property	*Slate*	*Ebony Asbestos*
Dielectric strength, approximately	25 volts per mil	50 volts per mil
Impedance, relative	1	6 to 8
Dielectric loss, relative	20	1
Max. temperature	above 200 C	100 C
Water absorption in 24 hours	0.15 to 2%	0.1%
Arc resistance	good	poor
Tensile strength	3,600 lb sq in.	2,000 lb sq in.
Transverse strength	9,500 lb sq in.	4,000 lb/sq in.
Compressive strength	10,250 lb/sq in.	15,000 lb/sq in.
Impact strength	Test results erratic, but slate more likely to be brittle.	

1. Ebony asbestos is easier to machine than slate. Care must be exercised in the drilling of slate, as holes chip when the drill passes through the slate. Slate bases should always be drilled from the front. Ebony asbestos bases may be drilled from the front or the back.

2. Ebony asbestos absorbs less moisture than slate. For this reason ebony asbestos is the preferred base material if panels are installed over or near an open body of water or in a humid atmosphere.
3. Slate is more brittle than ebony asbestos, which makes slate less desirable for panels subject to vibration or shock. Slate panels are more likely to be damaged by rough handling in transit or by dropping during shipment.
4. If an arc travels along the base between conductors of opposite polarity, slate is not decomposed by the arc. To re-establish the original insulating strength, it is merely necessary to wipe the arc path clean with a rag. Ebony asbestos is carbonized by the arc, and the carbon particles form a conducting path. To restore the insulating properties of the base, the carbon path must be removed by chipping or grinding. If conducting dust is likely to settle on a panel, with the resultant danger of arc-overs, slate is the preferred base material. For this reason, many steel mills insist on slate bases and refuse to accept ebony asbestos bases.

Panel Wiring

Most panels are wired in the back, although panels with backs that are inaccessible after they are installed may have to be wired in the front. Back-of-panel wiring is preferable from a manufacturing point of view. It is also preferable from the user's point of view since it leaves the front of the panel clean and makes it easier to service panel devices. Figure 199 is the back view of an open panel, showing control wiring, bus work, and terminal boards. The control wiring is laid on the bases and held in place by cleats. To permit separating the panel into sections for shipment, control wiring between panel sections is terminated at terminal boards on both sides of the vertical panel splits. Outgoing control connections are brought out to terminal boards at the bottom to facilitate connection of customer's control cables. On the panel shown, outgoing power connections are also terminated at power terminal boards. This arrangement makes it easy to bring power cables to the panel at the installation, especially in view of the large number of motor connections involved. However, the use of power terminal boards is not a generally accepted practice; in most cases power cables are connected directly to device studs on the panel.

For an example of a front-wired panel, see Fig. 200. This panel is fitted at the installation into the column of a machine tool, and the

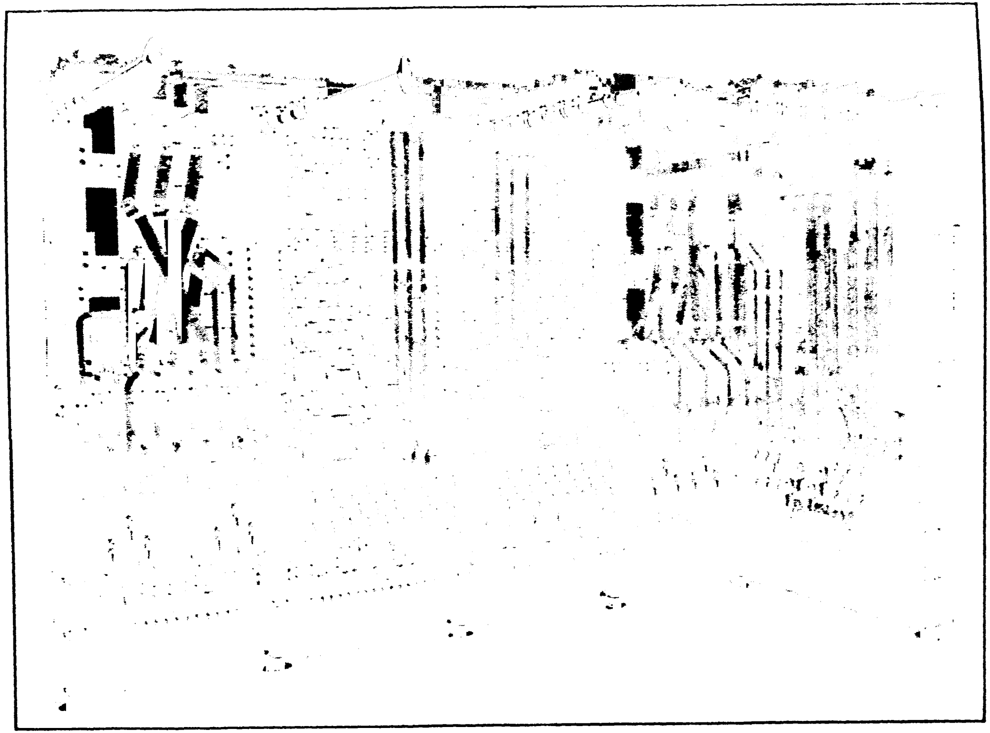

FIG 199 Back view of open control panel showing control wiring, bus work, and terminal boards

back is not accessible. To support the wiring and for neatness of appearance, a wiring trough is used which runs through the center of the panel and collects all vertical runs of control wiring. Terminal boards at the top and bottom take care of outgoing connections.

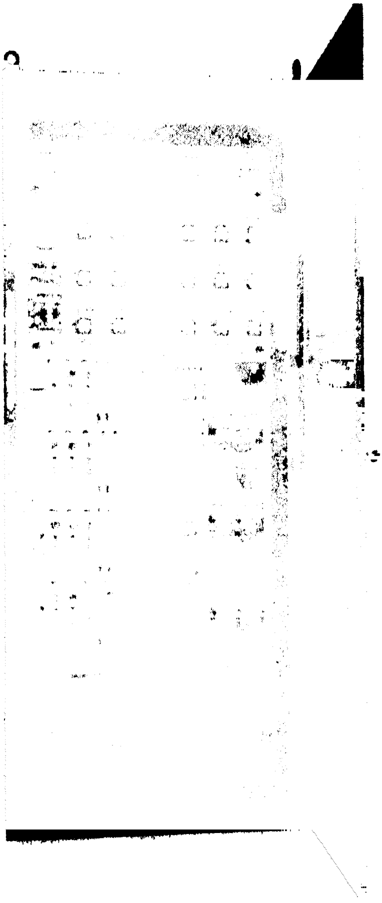

FIG. 200. Front-wired control panel.

Control connections on the panel are made with solid or stranded switchboard wire having a non-rubber insulation and an outer flame-resistant covering. Solid wire is somewhat easier to form and to support in straight runs. However, when stripping the insulation, the wireman may nick the wire, which is then likely to break under vibration. Panels mounted on moving structures, for instance cranes, are preferably wired with stranded control wire. No. 12 B & S gage wire has been generally accepted as a standard for control wiring. For panels built under wartime restrictions, No. 14 B & S gage wire has been substituted. On swinging panels, extra-flexible No. 16 B & S gage wire is used for control circuits carrying 5 amperes or less.

Power circuit connections are made either by bare copper bus bars or by insulated cable. Copper bus bars are less expensive to manufacture, but they are more difficult to support in long runs than cables, which may be bunched and laced together. The choice between bare copper and cable for power wiring is largely governed by manufacturing convenience.

Copper busses are made of flat or round copper bars. In Table 13 the continuous current-carrying capacity is given for copper bars of various sizes. The current rating applies to installation of busses in the open, with free air circulation around the bars and a permissible temperature rise of 40 C. An exception are the two smallest sizes of bars, ⅛ inch by ½ inch and ⅛ inch by ¾ inch. The current rating of these two sizes is determined by the requirements that a bar shall have a width of at least twice the diameter of the stud to which it is connected.

TABLE 13

CURRENT-CARRYING CAPACITY OF BARE COPPER BARS

Rectangular Copper Bar Size in Inches	*Continuous Rating in Amperes*	*Round Copper Bar Diameter in Inches*	*Continuous Rating in Amperes*
⅛ by ½	80	3/16	90
⅛ by ¾	150	¼	130
⅛ by 1	300	⅜	220
⅛ by 1¼	370	½	330
⅛ by 1½	440	⅝	440
⅛ by 2	570	¾	560
3/16 by 1½	520	1	820
3/16 by 2	700		
¼ by 1½	600		
¼ by 2	800		
¼ by 2½	1000		
¼ by 3	1200		
¼ by 4	1500		
2 × ¼ by 4 *	2400		
3 × ¼ by 4 *	2800		

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* With ¼-inch spacing between bars.

The current-carrying capacity of insulated cables is listed in Table 14. Ratings are based on the assumption that a single-conductor cable is used in free air. Two current ratings are listed. The second column designates the continuous current-carrying capacity as specified by the National Electric Code for cotton braided switchboard cable. An exception are the current values given for No. 14 and No. 12 wire, which are below the National Electric Code values. The third column of current values coordinates cable size and size of a-c motor in whose primary power circuit the cable is used. The National Electric Code requires that the current-carrying capacity of the cable is equal to at least 125 per cent of the continuous motor full-load current. Furthermore, the cable must be large enough so that it will not be damaged by either a short circuit or the stalled motor current which would blow a fuse having a rating of four times motor full-load current. The current ratings given in Table 14 must be reduced by 30 per cent when cables are bunched together.

TABLE 14

CURRENT-CARRYING CAPACITY OF CABLES ON PANELS

Cable Size	*Continuous Capacity in Amperes*	*A-C Motor Continuous Full-Load Current in Amperes*
No. 14	20	18
No. 12	30	25
No. 10	54	35
No. 8	71	50
No. 6	99	70
No. 4	133	100
No. 2	179	140
No. 0	245	196
No. 2/0	284	227
No. 3/0	330	264
No. 4/0	383	306
250,000 cm	427	342
500,000 cm	660	528
750,000 cm	846	677
1,000,000 cm	1000	800
1,500,000 cm	1260	1010
2,000,000 cm	1470	1180

When cables are used for power connections on a panel, consideration must be given to the choice of cable terminals. The available types, as illustrated by Fig. 201, are soldered terminal lugs, solderless connectors, and brazed terminal lugs.

Soldered terminal lugs are least expensive, and the connection is very satisfactory, provided a thorough soldering job is done. The skill and care of the workman influence the quality of the soldered joint. A poor joint with insufficient penetration of the solder may come apart when the cable carries load and heats up. This disadvantage is overcome by solderless connectors which depend on a mechanically clamped joint between cable and terminal. Various types of solderless connectors with an excellent service record are on the market. They are somewhat more expensive, and they may work loose under vibration. A brazed terminal consists of a lug which is pressure brazed to the end of the cable. The cable strands are fused together, forming a solid mass that is fused to the lug. With a properly designed fixture, the brazing process is independent of the skill of the workman. Although the brazed terminal has a less neat appearance than the other terminals, it provides the most reliable connection, both electrically and mechanically.

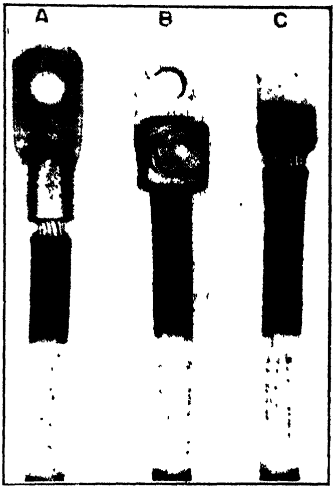


FIG. 201. Terminals for power cables on control panels. *A.* Soldered terminal lug. *B.* Solderless connector. *C.* Brazed terminal lug.

Open Control Panels

Floor-mounted panels are supported by pipe or angle iron uprights. Angle iron supports have come into greater use in recent years, primarily because multi-section panels can be split up more easily and angle iron supports fit better into enclosing cases. A support of popular size is 1½ inches by 2½ inches angle in heights of 64 inches, 76 inches, and 90 inches. Small panels, suitable for wall mounting, have supporting feet attached to each corner. Panels for assembly in cavities of machinery are usually supplied without any supports, and they are mounted on pads or studs forming part of the machine frame.

When devices are laid out on a control panel, the horizontal spacing of devices is governed by minimum clearances established by the Underwriters, given in Table 17 (page 398). Vertical spacing of contactors has to allow for sufficient distance between rows to prevent arcs from striking the contactors of the row above. Panels should not be filled down to the bottom, but at least 4 inches should be left between the floor and the bottom row of devices to permit sweeping of dirt from under the panel. Instruments should be arranged at eye level, and switches should be located so that an operator can reach them without stretching or bending down.

The arrangement of contactors is largely governed by the layout of power cables or bus bars. The fewer bends and crossings there are in the power wiring, the better the wiring job. Although a control panel is utilitarian rather than artistic, an orderly and well-balanced appearance assists the servicing electrician in orienting himself and in identifying the functions of the panel devices. Especially on large panels controlling a multiplicity of motors, a logical grouping of devices is of great assistance to maintenance men.

Each control panel presents its own problems, and no general recipe can be given on how to lay out panels. A point often overlooked and which cannot be sufficiently emphasized is the design of the back of the panel. Behind a large panel, a great many power and control conduits have to be arranged, and the control designer should find out the details of the installation work. Where to locate terminal boards, how to arrange for incoming and outgoing power cables, what facilities to provide for support of the contractor's cables, those are problems which should be studied jointly by the control design engineer and the installing contractor. The best solution will be obtained if the design engineer and the contractor cooperate closely in determining the details of panel design.

Panel devices should be marked both in the front and in the back. It can be done either by engraved nameplates or by painting the device designations used on the connection diagrams directly on the panel base. All outgoing power and control connections must be permanently marked, to agree with the connection diagram, by indelible stencils or stampings.

Open Frameworks

On large installations involving control of a multiplicity of correlated drives it is advantageous to combine a number of panels in a framework and to mount resistors, transformers, and other contingent equipment in the framework. A typical example is the framework of Fig. 202, which contains two rows of panels, mounted back to back. Resistors and other extraneous equipment are mounted on top, on both sides of a catwalk. All connections are made in the factory. At the installation the panel is set in place, fastened down, and the only connections to be made are incoming lines, motor leads, and outgoing control leads. Installation time and expense are greatly reduced thereby.

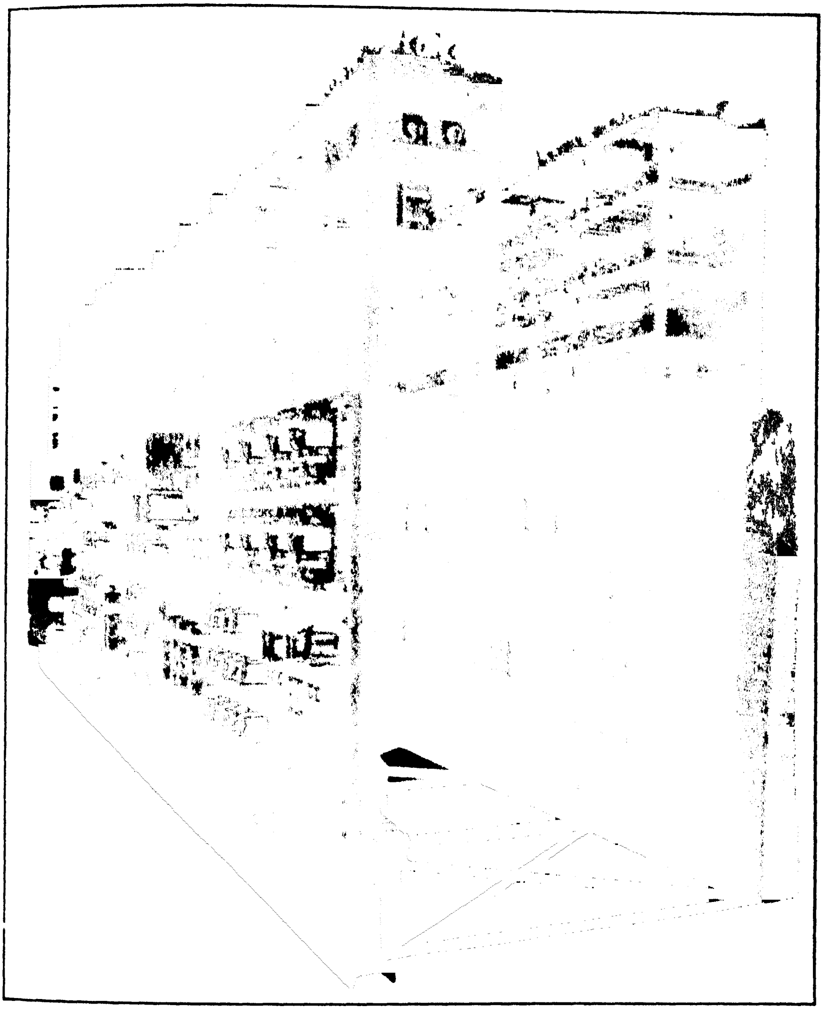


FIG. 202. Open panel framework with two rows of panels

Another example of a panel framework is given in Fig. 203. It accommodates one row of panels, with a bus structure overhead and resistors on racks in the rear. This method of construction obtains a clean and unobstructed aisle space in the back of the panels, making it easy for the electricians to service the panels. Note the method of lacing and supporting power cables in the back and the arrangement of outgoing motor terminals in clusters.

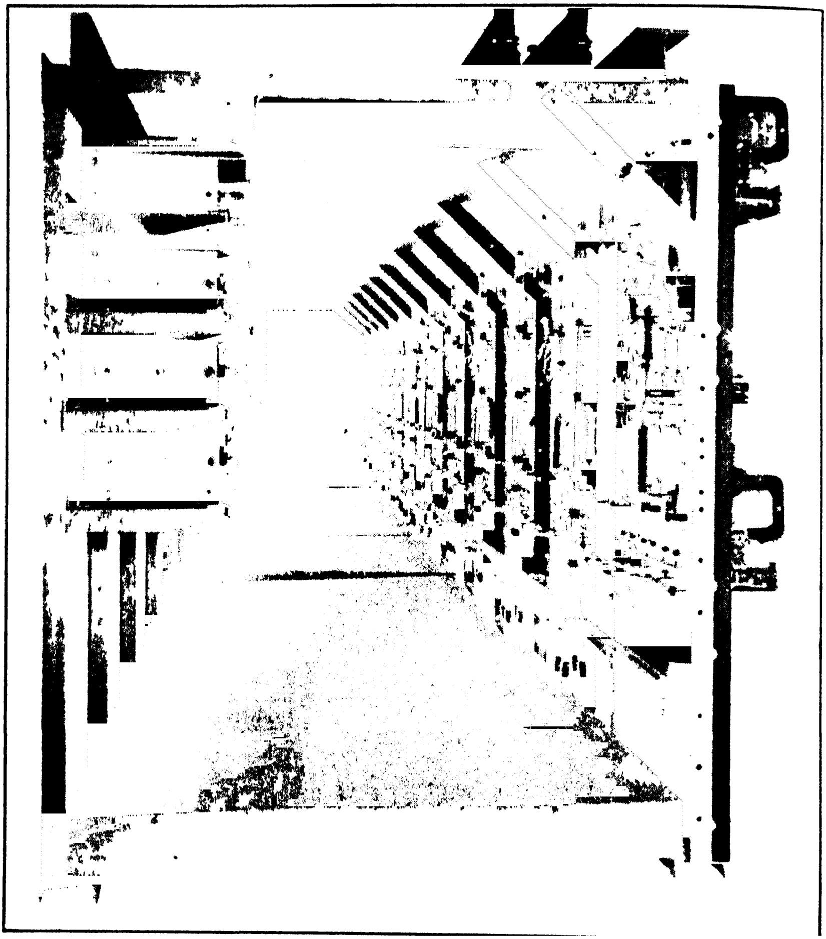


FIG. 203. Open panel framework with single row of panels and resistors in back.

Enclosing Cases, Classification [1, 4]

Control panels may be enclosed in sheet metal or cast cases. From an application point of view, enclosures are required for the following reasons:

1. To protect operating personnel from coming in contact with live parts of the control panel. This protection is important when

panels are installed near machinery in plants where unskilled workmen may come in contact with current-carrying parts, especially in crowded quarters.

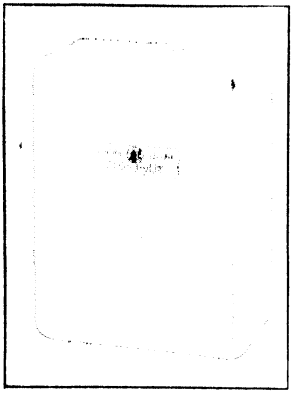
2 To protect the control apparatus against the effect of atmospheric conditions. Examples are protection against dust, dirt, splash and drip water, or corrosive fumes.

3 To protect adjacent apparatus and operators against the effects of explosions which may be touched off by electric arcs. In this category fall explosion-proof controllers for installation in coal mines or in atmospheres charged with explosive gas mixtures.

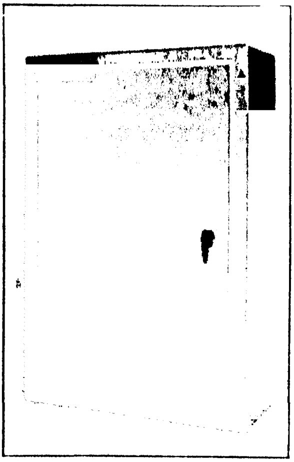
NEMA has established designations for standard types of enclosures, specifying the type of service for which the enclosures are suitable. These type designations, accepted by the trade, are found in standard descriptions and specifications of control manufacturers. Enclosures are either non-ventilated or ventilated. Ventilation is used if heat-dissipating apparatus, such as resistors, reactors, or transformers, are included in the enclosure and ventilating air is necessary to carry away the generated heat. Type designations for ventilated enclosures are the same as for non-ventilated ones, except that the type number is followed by the word "ventilated."

Type I covers general-purpose sheet metal enclosing cases designed to meet general requirements as laid down in the industrial control equipment standards of the Underwriters' Laboratories, Inc., as may be in effect from time to time. The principal purpose of type I cases is to protect against accidental contact. They are suitable for installation indoors and where atmospheric conditions are normal. A certain protection against dust and light indirect splashing is afforded, but the cases cannot be considered as dust-tight or splash-proof.

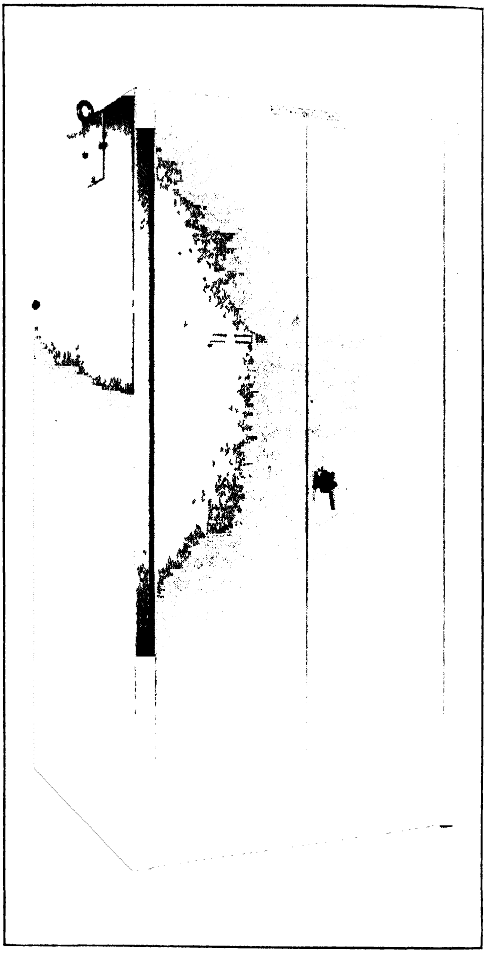
Shown in Fig. 204 are several type I enclosing cases. The drawn shell case is used for small contactors and starters. Its halves are punched with a deep drawing die, and the front cover slips over the back part of the case. Wall-mounted cases are fabricated of sheet metal by shearing, bending, and welding. The back of the case is solid, which means that outgoing panel connections must be terminated in the front. A hinged front door provides access to the panel. Floor-mounted cases are also fabricated of sheet steel, and by proper bending of the sheets into channel and angle sections, sufficient rigidity can be obtained to make a supporting framework unnecessary. Angle iron uprights support the weight of the panel, and the cases are designed so that they can be slipped over the panel. Floor-mounted panels have doors or removable covers in front and back. Both the front and the back of the panels are thus accessible. Outgoing connections are made in the back.



Drawn shell.



Wall-mounted.



Floor-mounted.

FIG. 204. Type I general-purpose enclosing cases

Enclosed panels, lined up side by side, can be built into continuous switchboards, forming a control center for extended equipment. Instruments, indicating lights, and pilot switches may be mounted in the doors of the enclosures. Illustrated in Fig. 205 is a dead-front switchboard, formed by a line-up of individual enclosed panels. All

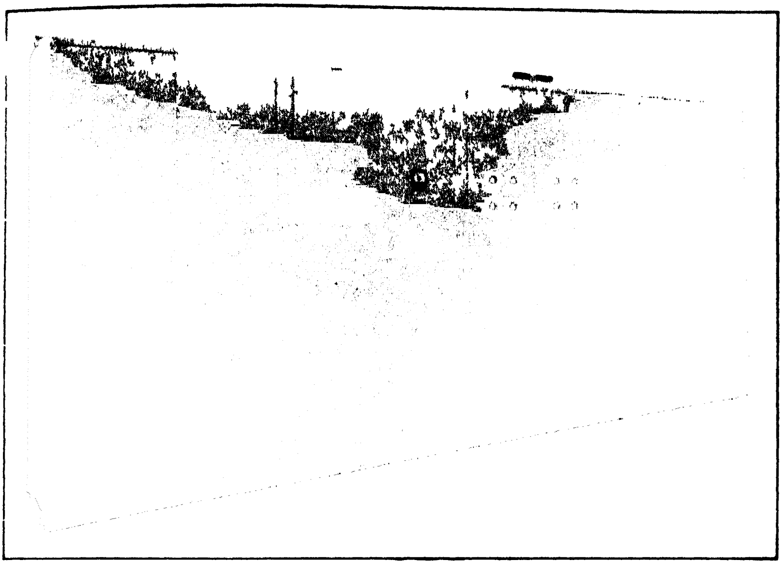


Fig. 205. Type I enclosed panels lined up to form a dead-front switchboard

Fig. 206. Method of wiring to devices in door of enclosing case

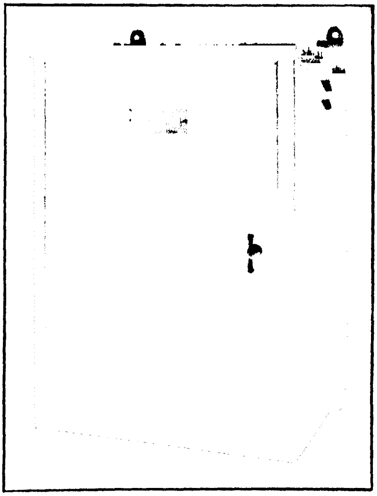


Fig. 207. Type II driptight enclosing case

devices which the attendant needs to operate the equipment are located in the doors. Contactors, relays, and open switches are behind the doors so that they are accessible to authorized maintenance crews, but the regular operators are protected against accidental contact with current-carrying parts. When devices are mounted in the doors, extra-flexible cable is used for wiring to the devices, and the loops are anchored around the door hinges to prevent breaking of wires due to the flexing that occurs when the doors swing open or closed. Figure 206 shows the details of one method of wiring. The flexible wiring is anchored by grommet plates on both sides of the hinge and terminated at a terminal board on the hinge. Solid wire is used from the terminal board to the device terminals.

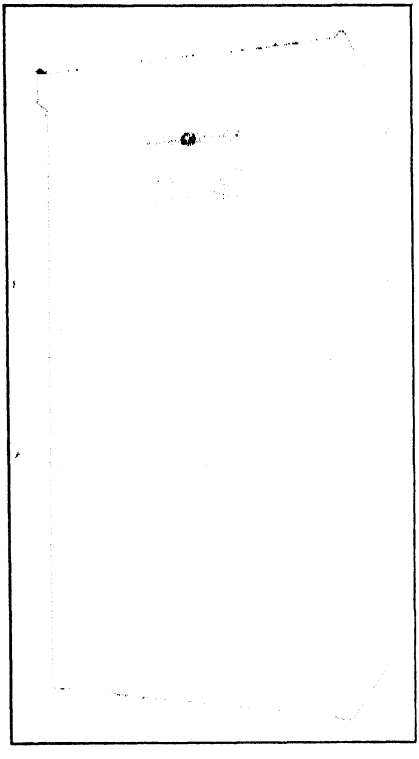


Fig. 208. Type III weather-resistant enclosing case.

A variant of the general-purpose type I case is obtained by placing a gasket around the cover or door. Such cases are recognized by NEMA as type IA. Panels in type IA cases are suitable for installation indoors, and the gaskets obtain additional protection against dust, although the cases are not considered dust-tight. They have become known to the trade as semi-dust-tight. Another variant is the type IB case, which is flush-type, designed for mounting in a wall and provided with a cover which serves as the flush plate.

Type II are driptight cases, made of sheet metal, but with added drip shields or their equivalent. They are suitable for installation in localities where condensation may be severe, such as in cooling rooms or laundries. Figure 207 is a typical drip-proof case. The top is sloping and overhangs the case door so that drip water runs off without entering the case around the door.

Type III cases are weather-resistant. They may be of cast construction or of sheet metal, with proper protection against weather

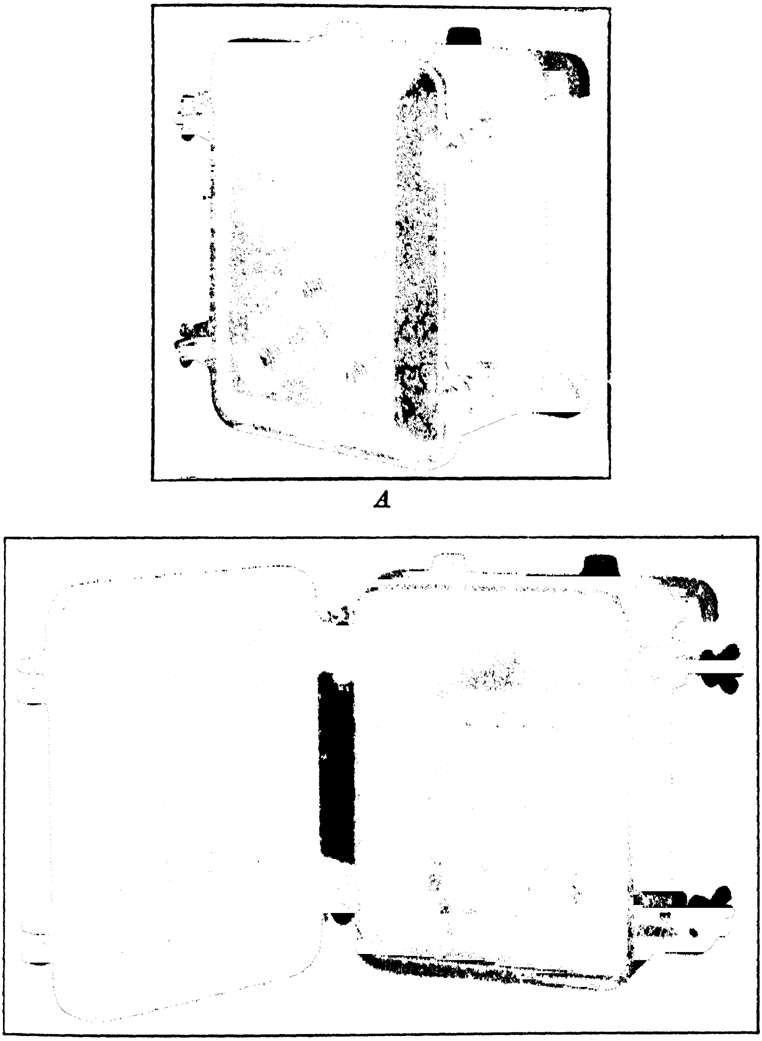


Fig. 209. Type IV watertight enclosing case A. Door closed. B. Door open

hazards, such as sleet and rain. A typical outdoor case is shown in Fig. 208. The case proper is fabricated of sheet metal, with drip shields over the doors. Inside the case a gutter is provided around the doors so that any rain water which may be driven by wind into the door cracks will collect and drain off without touching the panel inside. On top of the case is a resistor compartment, and all joints between the top compartment and the case top are gasketed to pre-

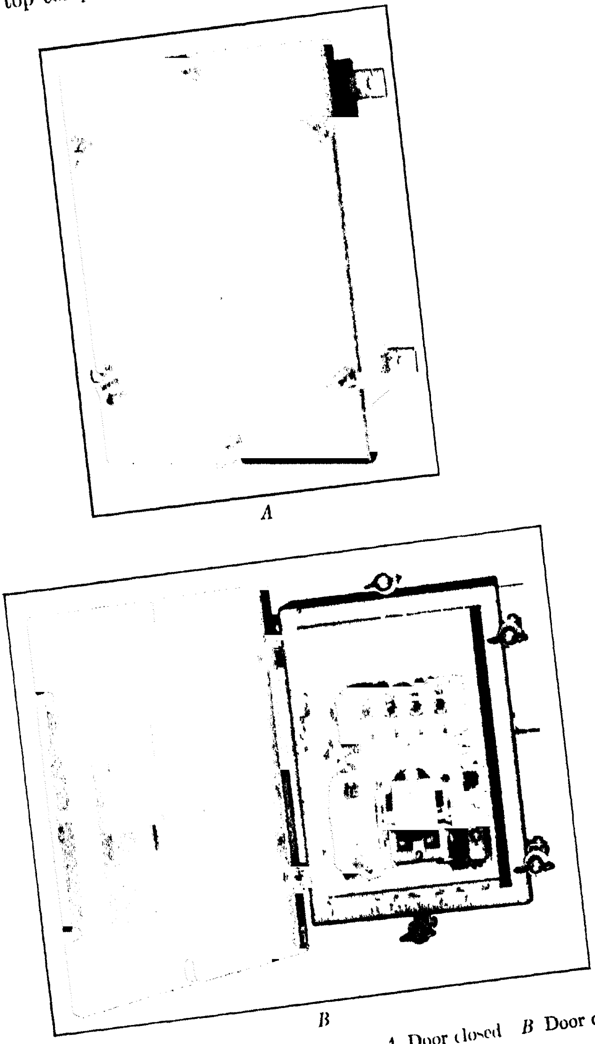


Fig. 210 Type V dust-tight enclosing case. A. Door closed B Door open.

vent water from entering the case at the top. The resistor compartment is covered by an overhanging sloping roof.

Type IV cases are watertight. They may be cast or fabricated of sheet metal. They are suitable for use outdoors, on docks, or in

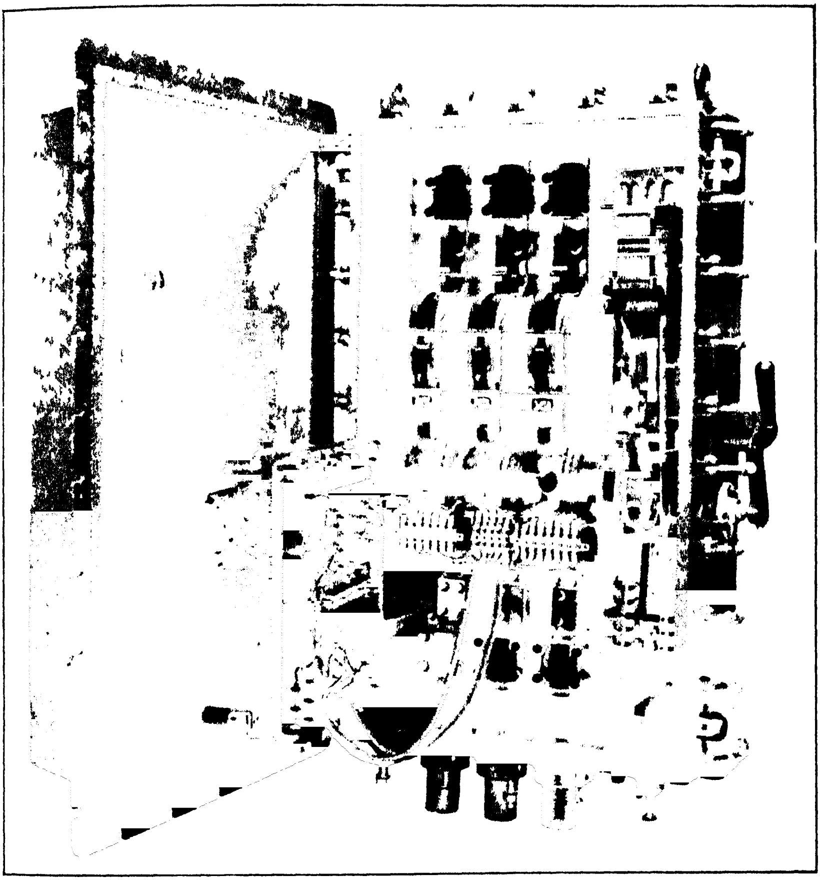


FIG. 211 Type VI submersible enclosing case

dairies, breweries, or paper mills, where the controllers may be hosed down for cleaning. A type IV case must stand the standard hose test. A stream of water from a hose not less than one inch in diameter, and delivering at least 65 gallons per minute, is played on the controller for five minutes from a distance of not less than 10 feet. No water must enter the enclosing case. The starter of Fig. 209 is enclosed in a type IV cast iron case. The cover is rubber gasketed and held tight with wing nuts. Start and stop push buttons, built into the starter, and the overload reset button are operated from the outside through bellows welded to the case cover.

Type V cases are dust-tight and so constructed that dust will not enter the enclosure. They are used in steel mills, cement mills, and other locations where the atmosphere is heavily charged with dust. The enclosing case of Fig. 210 is fabricated of sheet metal. The cover is hinged and gasketed and held tight by wing nuts, which however are spaced farther apart than on watertight cases. The reset button for the overload relay protrudes through the cover.

Type VI cases are submersible. They are constructed so that the apparatus enclosed within operates successfully when the whole controller is submerged in water. Such cases are intended for use in such locations as quarries, mines, or manholes. The pressure and the length of time of submersion must be specified for any given application. A submersible enclosing case is illustrated in Fig. 211. It is fabricated of heavy gage sheet metal. The cover is gasketed, and it is held tight by closely spaced wing nuts. Shafts extending through the side, for instance for switch operation, are carried through a stuffing box. Bushings are provided for the incoming power cables. Wiping joints for cable connections are desirable, although not compulsory.

Type VII cases are designed for hazardous locations, class I, air break. They are designed to meet the requirements of the National Electric Code for Class I, Group D Hazardous Locations and the requirements of the Underwriters' Laboratories specifications. Air break apparatus is used.

Type VIII cases are designed for hazardous locations, class I, same as type VII, except that the apparatus is immersed in oil.

Type IX cases are designed for hazardous locations, class II, in accordance with the National Electric Code and the Underwriters' Laboratories specifications.

The specific requirements laid down for class I and class II hazardous locations are discussed in detail under the heading "Controllers for Hazardous Locations."

Type X cases are designed to meet the requirements of the U. S. Bureau of Mines, especially for application in coal mines. The specific design details are given under the heading "Bureau of Mines Controllers."

Design of Enclosing Cases [1]

NEMA, Underwriters' Laboratories, and the National Electric Code have established certain stipulations governing the design of enclosures. The following is quoted from the NEMA Industrial Control Standards as being the most applicable guide to the design of enclosing cases for industrial control equipment.

1. All enclosures shall be so designed and assembled that they will withstand handling during shipment and installation.

2. There must be sufficient space within the enclosure to permit uninsulated parts of wire terminals to be separated so as to prevent their coming in contact with each other. Enclosures must be such as to permit proper wire connections to be made with adequate spacing of the terminals and ends of conductors from adjacent points of the enclosure.

3. Exposed non-arcing current-carrying parts within the enclosure shall have an air space between them and the uninsulated walls of the enclosure, including conduit fittings, of at least ½ inch for 600 volts or less Enclosures of sizes, material, or forms not securing adequate rigidity must have greater spacing. A suitable lining of insulating material not less than 1/32 inch in thickness may be considered acceptable where the spacing referred to above is less than ½ inch. The clearances between exposed non-arcing current-carrying parts within the enclosure and other conducting parts which may be connected to the enclosing case, such as heads of mounting screws, shall conform to Table 15.

TABLE 15

CLEARANCES AS SPECIFIED BY NEMA STANDARDS

Rating In Volts	Distance in Inches Through Air	 Through Oil	 Across Clean Dry Surface Air	 Across Clean Dry Surface Oil
51–150	⅛	⅛	¼	¼
151–300	¼	¼	⅜	⅜
301–600	⅜	⅜	½	½
601–2500	1	¾	2	1
2501–5000	2	1½	3½	2

Note. The clearance distance should be increased for dirty or moist conditions.

Exception. For fractional horsepower controllers and other small devices, 300 volts or less, where the enclosure is rigid, an air space of ¼ inch is permitted between non-arcing current-carrying parts and the uninsulated part of the enclosure.

4. All enclosures and parts of enclosures such as doors, covers, tanks, etc., shall be provided with means for firmly securing them in place. Among the available means are locks, interlocks, screws, and seals.

5. A flush type enclosure for mounting in a wall shall be provided with adjustment to align the device with the flush plate and to compensate for differences in thickness of the wall finish.

Electrical Clearance and Creepage Distances

1. The distance between non-arcing, uninsulated live parts of opposite polarity and between non-arcing, uninsulated live parts and parts other than the

enclosure which may be grounded when the device is installed shall not be less than given in Table 15. (In this connection, refer also to Table 17, page 398

2. The spacings in snap switches, lamp holders, and similar wiring devices supplied as part of industrial control equipment need not comply with the requirements of the aforesaid standards provided such devices are not employed in the motor circuits.

Material for Enclosing Cases [1]

The following requirements concerning materials used in the construction of enclosing cases are quoted from NEMA Industrial Control Standards:

1. *Material.* In the following paragraphs it is assumed that steel (or gray iron for castings) will be the metal employed. Copper, bronze, and brass are sometimes used, in which case the requirements given for steel shall be complied with.

2. *Thickness of Casting.* Cast metal for enclosures, whether of iron or other metal, shall be at least ⅛ inch thick at every point and of greater thickness at reinforcing ribs and door edges, except that die-cast metal may not be less than 3/32 inch thick for an area greater than 24 square inches or having any dimensions greater than 6 inches. Cast metal shall be at least ¼ inch thick at threaded holes for conduit.

3. *Sheet Metal Thickness.* The minimum thickness required for sheet metal enclosures varies with the size. For solid enclosures without slot or other opening, and for solid enclosures except for a slot for the operating handles or openings for ventilation or both, the sheet metal shall be of gage not less than given in Table 16, except that metal shall not be less than No. 20 U.S.S. gage in thickness at points where rigid conduit is to be connected.

TABLE 16

MINIMUM THICKNESS OF SHEET METAL ENCLOSURES FROM NEMA STANDARDS

Maximum Volume of Enclosure in Cubic Feet	*Maximum Area of Any Surface in Square Inches*	*Maximum Dimension in Inches*	*Minimum Thickness without Supporting Frame*	*U. S. Standard Gage with Supporting Frame or Equivalent Reinforcing*
¾		12	20 (0.037 in.)	24 (0.025 in.)
1		18	18 (0.050 in.)	20 (0.037 in.)
	360	24	16 (0.062 in.)	18 (0.050 in.)
	1200	48	14 (0.078 in.)	16 (0.062 in.)
	1500	60	12 (0.109 in.)	16 (0.062 in.)
	Over 1500	..	10 (0.141 in.)	16 (0.062 in.)

4. All enclosures of wire mesh, perforated screens, or grille work shall be provided with a supporting frame.

5. Ventilating openings in an enclosure, including perforated holes, louvers, and openings protected by means of wire screening, expanded metal, or per-

orated covers, shall be of such size or shape that no opening will permit passage of a rod having a diameter greater than ½ inch; except that when the distance between live parts and the enclosure is greater than 4 inches, openings may be larger than those previously mentioned, provided that no opening will permit passage of a rod having a diameter greater than ¾ inch. The wires of a screen shall be not less than No. 16 Awg when the screen openings are ½ square inch or less in area, and shall be not less than No. 12 Awg for larger screen openings.

Except as noted in the following paragraph, sheet metal employed for expanded metal mesh, and perforated sheet metal shall not be less than No. 18 U.S.S. gage in thickness when the mesh openings or perforations are ½ sqpare inch or less in area, and shall be not less than No. 13 U.S.S. gage in thickness for larger openings.

In a small device where the indentation of a guard or enclosure will not affect the clearance between uninsulated, movable, current-carrying parts, and grounded metal, No. 24 U.S.S. gage expanded metal mesh may be employed, provided that (*A*) the exposed mesh on any one side of the surface of the device so protected has an area of not more than 72 square inches and has no dimension greater than 12 inches or that (*B*) the width of an opening so protected is not greater than 3.5 inches.

6. The requirements of enclosures for floor-mounted controllers for voltages not in excess of 600 volts shall be:

(I) Where the surrounding enclosure is 6 feet or more in height and exposed live parts are not less than 6 inches below the upper edge, no covering is required across the top of the enclosure.

Exception. Where cranes or other movable apparatus or operations of a special character may introduce possible hazards from above, overhead enclosures may be required.

(II) Where the surrounding enclosure is within 6 inches of the floor and exposed live parts are not less than 6 inches above the lower edge, no covering will be required for the bottom.

Controllers for Hazardous Locations [2]

The National Electric Code has established classifications for various kinds of hazardous locations. The most important ones are as follows:

Class I locations are those in which flammable volatile liquids, highly flammable gases, mixtures, or other highly flammable substances are manufactured, used, handled, or stored in other than their original containers. The following tabulation gives a list of manufacturing plants, parts of which may fall in the class I category:

Dry-cleaning.
Dry-dyeing.
Pyroxilin-plastics manufacture.
Spray-painting.
Flammable-gas manufacture.

Varnish manufacture.
Distilleries.
Rectifying and blending alcoholic liquors.
Industrial alcohol manufacture.

Although this listing is not complete, it serves as a guide to types of hazardous processes falling under class I locations.

Class II locations are those in which combustible dust is thrown, or is likely to be thrown, into suspension in the air in sufficient quantities to produce explosive mixtures. Or class II locations may be those where it is impracticable to prevent such combustible dust from collecting in such quantities on or in motors, controllers, lamps, or other electric devices that they are likely to become overheated because normal radiation is prevented. Typical class II locations are found in:

Flour mills.
Grain elevators.
Starch plants.
Sugar mills.
Cocoa mills.
Coal-pulverizing plants.

Under each class, various groups are established, depending on the severity of service. To reduce the number of standard types of enclosures, NEMA recognizes group D as the one most applicable to enclosures for controllers in hazardous locations.

The Underwriters' Laboratories list two types of construction for enclosures used in class I, group D harazardous locations. One is the "air break" type (NEMA type VII) and the other is the "oil-immersed" type (NEMA type VIII).

Class I, group D air break type enclosure specifications are based on the assumption that explosive gas will seep into the enclosure. Experience and laboratory tests have proved that absolutely gastight enclosures are impracticable, since necessary joints cannot be maintained permanently in a gastight condition. A slow infiltration of explosive vapors must be expected, and such vapors may also enter the enclosure when the equipment is being serviced. Thus an explosion inside the enclosure is expected, and the enclosure must be designed so that it will resist the explosive pressure by its strength and will prevent the escape of flame through joints, operating shaft openings, screws, rivets, and conduit openings. Explosion pressures may range between 75 and 130 pounds per square inch, depending upon the size and shape of the enclosure, its free internal volume, and the nature of the gas mixture. Enclosures are either cast or fabricated of heavy steel boiler plate.

The salient features of class I, group D air break construction, as stipulated by the Underwriters' Laboratories, are as follows. No fuses are permitted. Cast cases must withstand, without rupture or permanent distortion, a hydrostatic pressure test of four times the maximum internal explosion pressure developed during an explosion test. The hydrostatic test may be omitted if calculations show that the case has a factor of safety five times the explosion pressure. Fabricated cases must withstand two times explosion pressure without permanent deformation and three times explosion pressure without rupture.

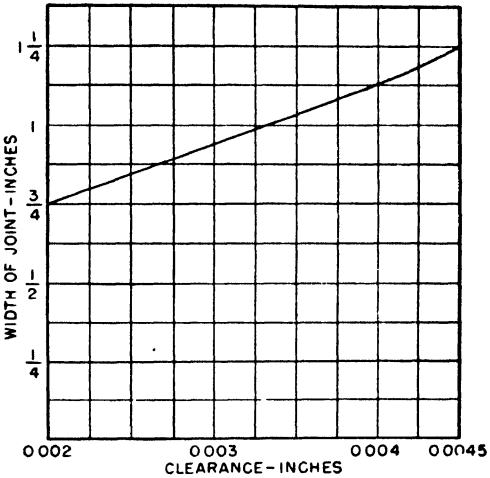


FIG. 212. Clearance of joints for class I, group D enclosing cases.

Joints must be metal to metal and never less than ¾ inch in width, except with rabbet joint, and not over 300 cubic inches, volume, in which case the width may be ½ inch with 0.002-inch clearance. The permissible clearance of flat joints of various widths is plotted in Fig. 212. The diameter of bolt holes must be not more than 1/32 inch larger than the diameter of the bolt, and the distance from the bolt hole to the inside of the enclosure must be not less than one half the width of the flange. Shafts through the enclosure wall must be at least one inch long with 0.0033-inch maximum clearance, or 1⅛ inch long with 0.004-inch clearance, or 1¼ inch long with 0.0045-inch clearance. Outgoing connections must be made through threaded joints having at least five full threads. The use of sealing compounds is recommended. The compound applied must be impervious to hazardous vapors, and its softening point must not be below 200 F.

A typical NEMA type VII enclosure, class I, group D air break construction, is shown in Fig. 213. The case is cast with wide flanges and long sleeves are provided for the shafts through the enclosure.

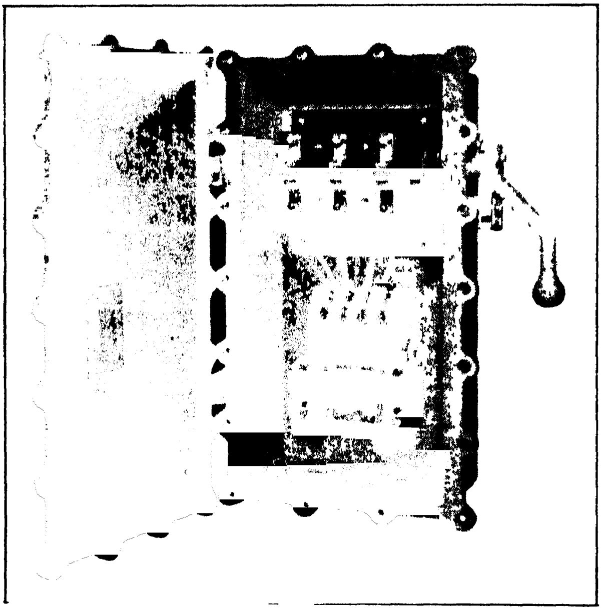


FIG. 213. Type VII class I, group D enclosing case, air break type, for hazardous locations.

Class I, group D oil-immersed type enclosure specifications are based on the theory that all electric contacts, joints, and any other parts that might produce a spark are located under oil, so that arcs or sparks occurring within the oil will not ignite any flammable atmosphere that may accumulate within the enclosure above the oil level. As no explosion can occur within the enclosure, it is not necessary for the tank to withstand explosion pressures.

The Underwriters' Laboratories require for this type of enclosure that all connections, joints, terminals, and arcing parts are at least 6 inches below the normal oil level. Auxiliary devices, used in control circuits only, may be located 2 inches below the oil level. An oil level indicator must be provided. A typical NEMA type VIII enclosure is shown in Fig. 214.

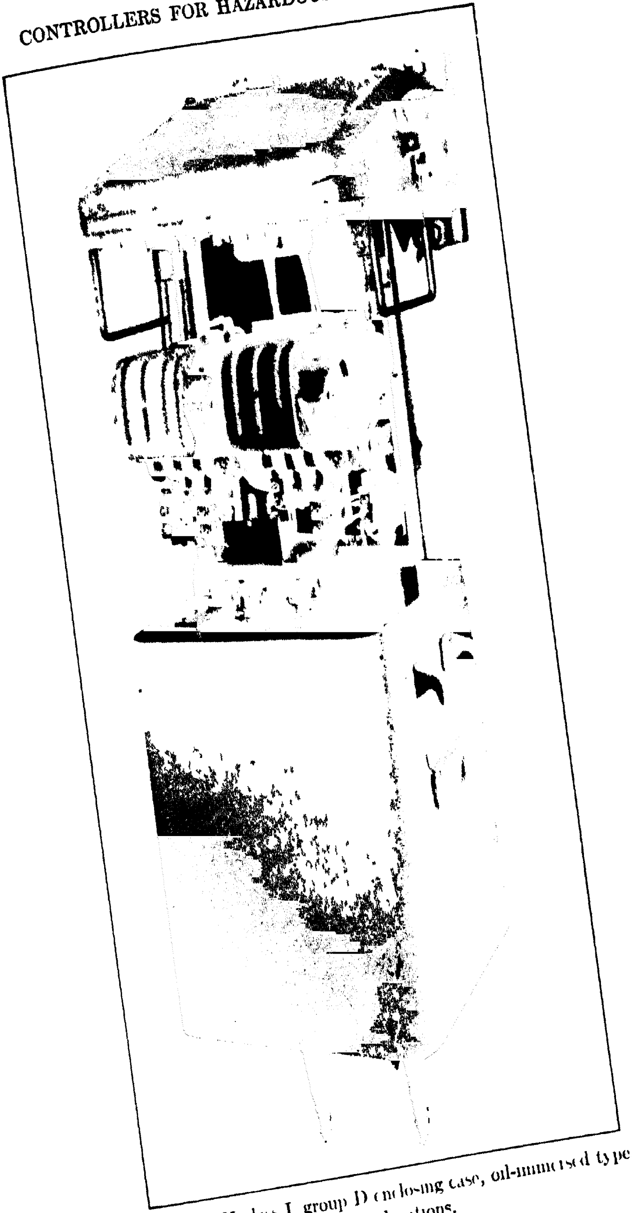


Fig. 214. Type VIII class I, group D enclosing case, oil-immersed type, for hazardous locations.

Although type VII (air break) and type VIII (oil-immersed) enclosures are equally suitable for use in hazardous locations, several factors may influence the selection of one type in preference to the other. The presence of corrosive fumes makes the use of oil-immersed equipment advisable, as the oil protects against corrosion. As the enclosure of air break type controllers must be designed to withstand high pressures, there are definite limitations to the size of enclosures that can be built, and size of equipment may dictate the selection of an oil-immersed type. Some devices are not suitable for operation under oil, and this may demand the selection of an air break type. The life of contact tips in air is many times the life of contact tips operating under oil. For controllers which are called upon to operate frequently, the air break type has the advantage of longer contact life.

Class II, group D (NEMA type IX) enclosures are required to be designed so that dust does not enter, and joints must provide a tight fit. Metal-to-metal joints must be at least 3/16 inch wide. Gaskets may be used, and the minimum contact width must be 3/8 inch. The use of rubber is not permitted. Gaskets must not be glued, but they must be attached to the box or the cover by mechanical fastenings. Shaft openings must be at least 1/2 inch long with 0.005-inch maximum clearance, or 1 inch long with 0.008-inch maximum clearance. Outgoing connections must be threaded, the threading being at least 1/4 inch deep.

Enclosures may be either of cast iron or they may be fabricated of sheet steel. Cast cases usually have metal to metal joints, whereas fabricated cases use gaskets. Most air break type VII cases meet the requirements of class II use. Oil-immersed type VIII enclosures must be made dust-tight to meet class II specifications.

Bureau of Mines Controllers [3, 5]

The United States Bureau of Mines has issued specifications for explosion-proof mine equipment which govern the design of controllers for use in coal mines. The salient requirements which apply to the design of NEMA type X enclosures are:

A main entrance switch must be provided, or its equivalent such as a line contactor or circuit breaker. On portable machines, each ungrounded conductor of the trailing cable must be protected against overload and short circuit by a fuse or other automatic circuit-interrupting device. Every motor must be protected against overload by an automatic circuit-interrupting device. If on direct-current controllers the terminals are properly marked, protection is required only in the ungrounded line. On three-phase circuits, two-element overload relays are permissible if the third phase is fused. Overload relays, which do not protect against short circuits, are permissible, if fuses are also used.

Cases should have a wall thickness of at least $\frac{3}{16}$ inch. Cases may be tight, or they may be ventilated, although ventilation is not recommended. Cases must be designed to withstand explosion pressures, which may be as high as 100 pounds per square inch. Flanges must have metal-to-metal contact. If the volume of the case is more than 60 cubic inches, a one-inch flange width or a $\frac{3}{4}$-inch rabbet joint is to be used. For cases with a volume of less than 60 cubic inches, a $\frac{3}{4}$-inch flange may be used, but a one-inch flange or $\frac{3}{4}$-inch rabbet joint is recommended. A maximum gap of 0.004 inch over a distance of less than 6 inches is permissible, provided a discharge of flame does not occur during an explosion test.

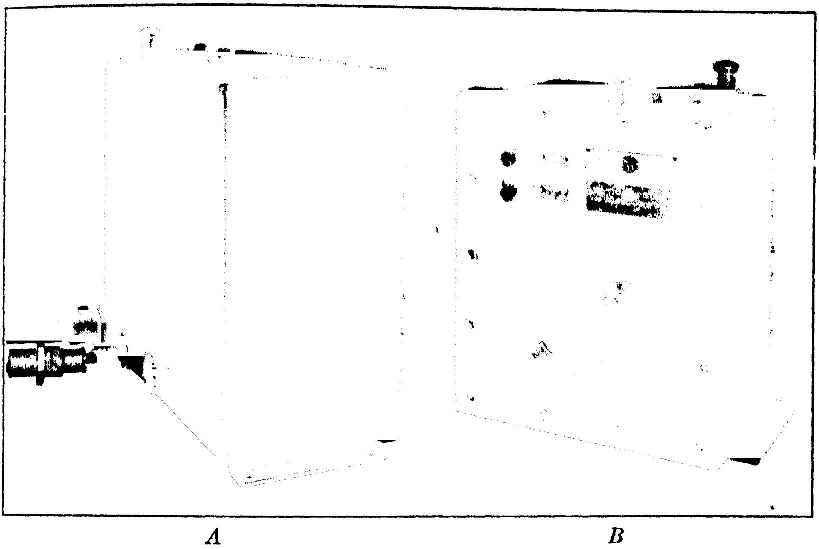


FIG. 215. Type X enclosing case, Bureau of Mines construction, for use in coal mines. *A*. Back view. *B*. Front view.

Lead entrances may be insulated studs, shielded with insulating barriers. If stuffing boxes are used, the packing material is asbestos which, when compressed, must completely surround the wire or cable for a distance of not less than $\frac{1}{2}$ inch. Sealing compound is permissible if the design of the stuffing box is such that the compound will not crack or flow.

Shown in Fig. 215 is a NEMA type X controller, meeting U. S. Bureau of Mines specifications. In the case cover is a handhole with screwed-in cover to permit access to the line fuses. The handhole cover is sealable. A start-stop push button is operated through buttons in the front cover. The handle in the top actuates the motor-reversing switch.

To prove the design of the enclosure, it is subjected to an explosion test conducted by the Bureau of Mines at its experimental station. The case is filled with explosive gas, and it is set up in a chamber which is also filled with explosive gas. The gas inside the case is exploded by a remotely operated spark, and the case is considered unsatisfactory if (1) flame is discharged from any joint or opening; (2) the surrounding explosive gas mixture is ignited; (3) dangerous after-burning occurs; (4) explosive pressure above 150 pounds per square inch is observed.

Control Centers [6, 7]

When magnetic control was introduced in manufacturing plants, starters and other small controllers were mounted on walls and building columns in a more or less haphazard fashion, making it difficult to supervise and maintain them. Later, starters and other controllers were grouped on walls or on pipe and angle iron racks. Although this grouping was a step forward, making for better supervision and maintenance, a considerable amount of installation expense was incurred, as each controller had to be mounted and wired individually, requiring a great deal of conduit work to provide line busses and to interconnect controllers into an integrated control system.

Since 1940 a system of mounting individual controllers in a common structure has been developed, and is offered by several manufacturers. A typical example is shown in Fig. 216. The more popular sizes of controllers, full-voltage starters, reversing starters, circuit breakers, etc., are mounted on individual standardized frames, which in turn are mounted in compartments of a standardized type I enclosed structure. Line busses are carried in the top portion of the structure. This grouping of controllers presents a pleasing appearance, and its orderly and logical arrangement is conducive to good maintenance. Interconnections between starters and to the busses are made in the factory, saving expensive field wiring. Although the cost of a control center is higher than the cost of individual starters, the installed cost of a control center reflects an appreciable saving in installation expense, making it attractive from the point of view of cost done. Also, the manufacturer is doing a considerable amount of engineering in planning the overall layout, relieving the user of the necessity of planning the mounting and wiring of a multiplicity of control units.

By standardizing the size of controllers, size of compartments, and other structural elements, control centers can be built of units forming the building blocks. When a manufacturing plant expands, additional units can be added easily to an existing control center.

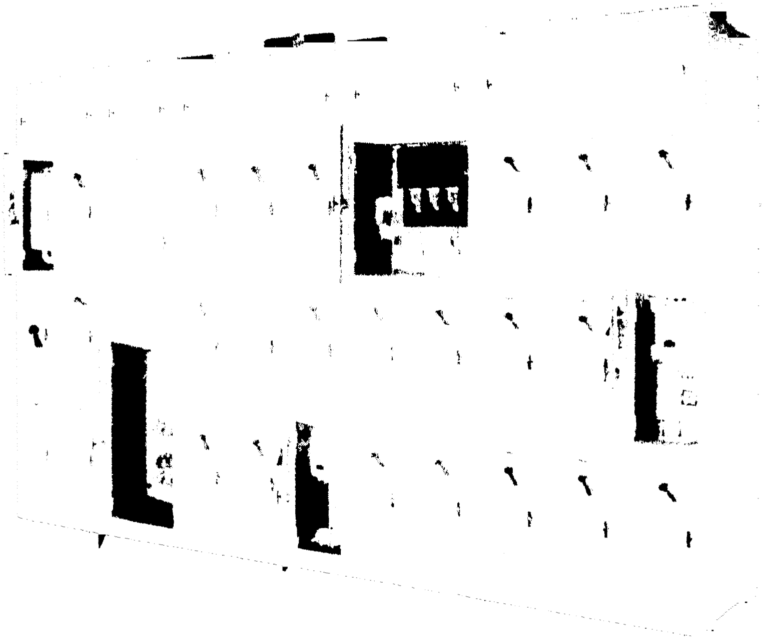


FIG. 216. Control center.

The whole structure is dead-front, and compartment doors can be locked. Thus a high degree of safety is assured to the operating personnel and tampering by unauthorized persons is prevented.

Draw-Out Controllers[7]

In central station practice, draw-out devices have become very popular because it is possible to remove a faulty device and replace it immediately with a spare device, without disconnecting and dis-

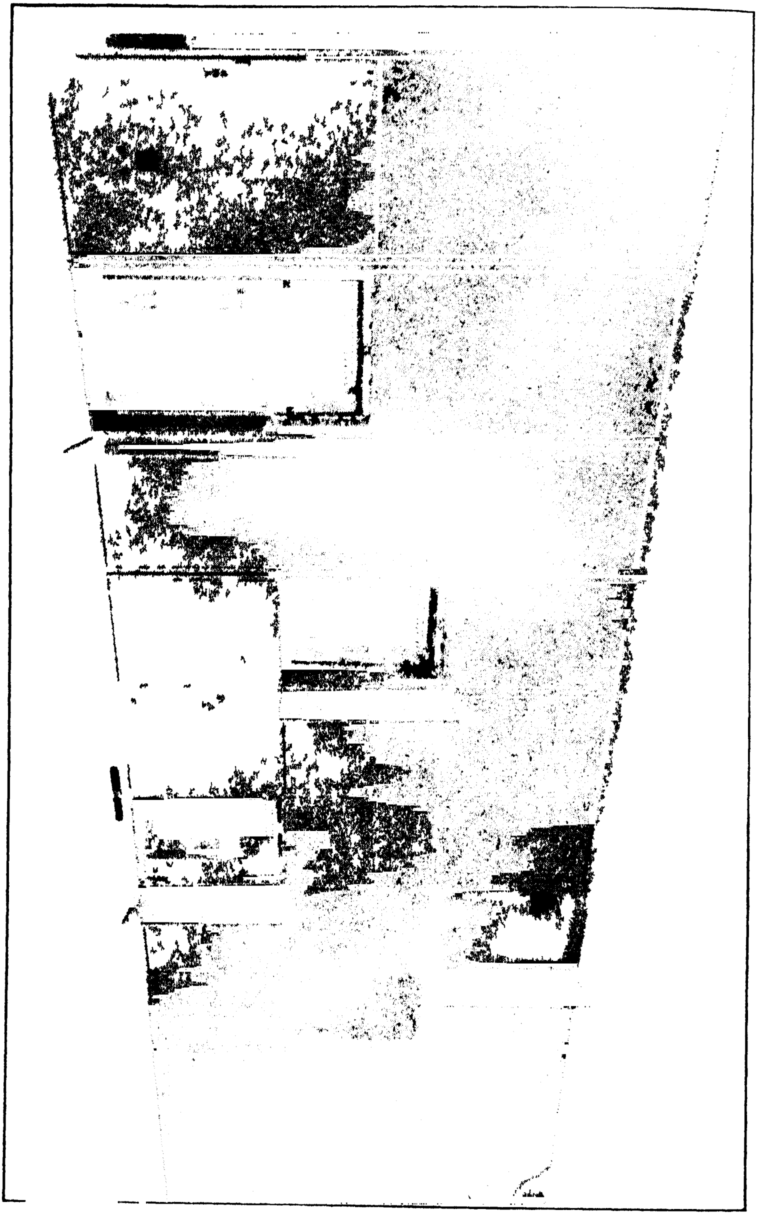


FIG 217 Draw out type control structure

assembling it. Although in control work, draw-out devices have not come into general use, draw-out type controllers have been built for applications on which a high degree of availability of the control equipment was specified.

Shown in Fig. 217 is a draw-out type control structure. It resembles a control center, except that each compartment houses a

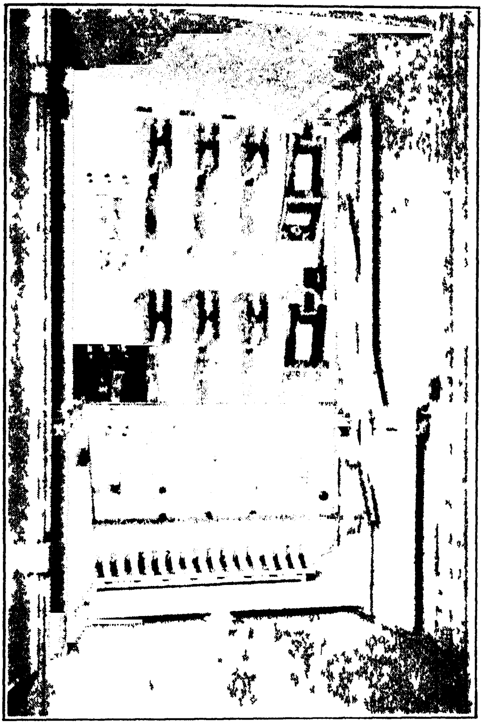


Fig. 218 Individual draw-out unit

draw-out type control unit. Figure 218 is a close-up of one unit, the equivalent of a full-voltage reversing starter. The magnetic devices are mounted on a base, which hangs on a sliding support. When the panel is pushed fully into the compartment, power and control connections are established through sliding connectors, engaging stationary contacts on the structure. By means of a lever mechanism, the base may be slid forward. As soon as the base starts to move, the power contactors are tripped out, so that the sliding power contacts part with no current flowing. In an intermediate position, the power connections are broken but control connections are re-established, so that the control functions of the controller can be tested without energizing the motor. In the extreme forward position, power and control connections are broken, and the controller may be removed from the compartment.

Draw-out construction permits removing a faulty controller and replacing it by a spare unit with a minimum interruption of service. Draw-out controllers are more expensive than any other design, but their additional cost may be acceptable in cases where continuity of service is of paramount importance, for instance, for powerhouse auxiliaries or for continuous manufacturing processes.

Operators' Panels and Control Desks

Many processing machines involve a considerable number of motors and auxiliary equipment which are under the control of a single operator. To supervise the equipment, the attendant requires a considerable number of pilot devices, such as push buttons, control switches, and in many cases instruments, pilot lights, and rheostats. On complicated drives, it is essential to have all these devices located in a small area and arranged in an orderly manner. Mounting the pilot devices individually on the machine would result in an expensive and haphazard installation. It is preferable to combine all pilot devices

FIG. 219. Operator's pilot control panels for a cold-strip mill.

on a single panel, which obtains better grouping and permits all necessary interconnections to be made on the panel.

Figure 219 is a view of a tandem cold-strip mill. On the first stand are mounted two operator's panels containing all pilot devices which the operator requires to control the mill. The left-hand panel contains push buttons, control switches, and pilot lights, with which the operator starts and stops the various motors on the mill. The panel is a wall-mounted case with pilot devices mounted in the front cover. Opening the cover gives access to the device contacts, wiring, and terminal boards. To the right is a second panel, containing rheostats to control the speed of various motors. The rheostats themselves are inside the box, with operating handles in the front. Access to the rheostat and the wiring is gained by removing the side plate. To the left can be seen an instrument panel containing the load and speed indicators in the front cover, which can also be swung open to expose the wiring.

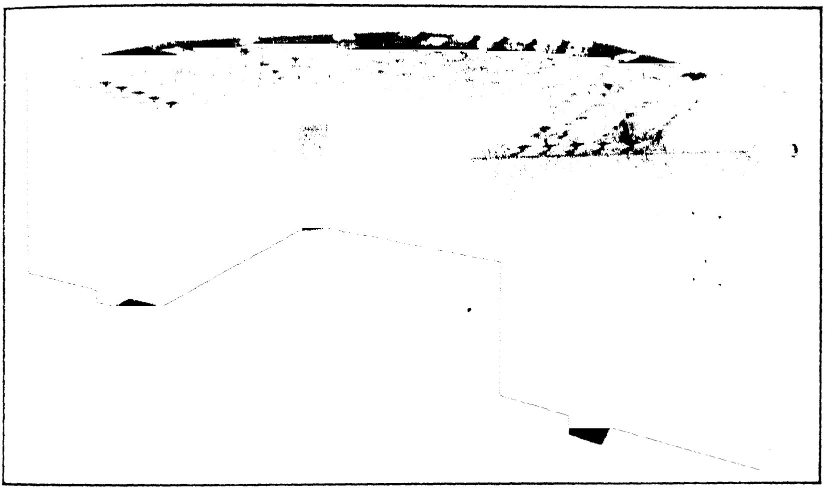


FIG. 220. Control desk for steel mill auxiliaries.

Motors, scattered over a wide area, may form an integrated operating unit. The operator is then located at a strategic spot, apart from any of the drives, but located so that he can observe the most essential functions. A control desk is a very satisfactory means of combining pilot devices, indicators, etc., in an arrangement that is easily supervised. As an illustration, Fig. 220 shows a control desk for the run-out tables and coilers of a steel mill. Numerous control switches, push buttons, rheostats, and instruments are located in a confined area, within easy reach of the operator. All interconnections between devices are factory assembled, without use of conduit. From the user's point of view, a control desk has the advantage that it is tested as a unit in the factory, where such testing can be done more accurately and with less effort than at the installation.

A control desk consists of a supporting frame and a top on which devices are mounted. Compound tops provide additional insulation for the devices. Steel tops afford greater safety to the operator, as all structural parts of devices are at ground potential. Control desk frames are fabricated of sheet steel, usually ⅛ inch thick, formed into channel and angle sections at the corners to provide adequate strength. Sharp corners are to be avoided, and all welds should be continuous and ground smooth to the contour of the bends, not only adding to the appearance but also minimizing the danger of tearing clothes. The inside of the desk should be accessible at least from the front and one side, to permit wiring and servicing.

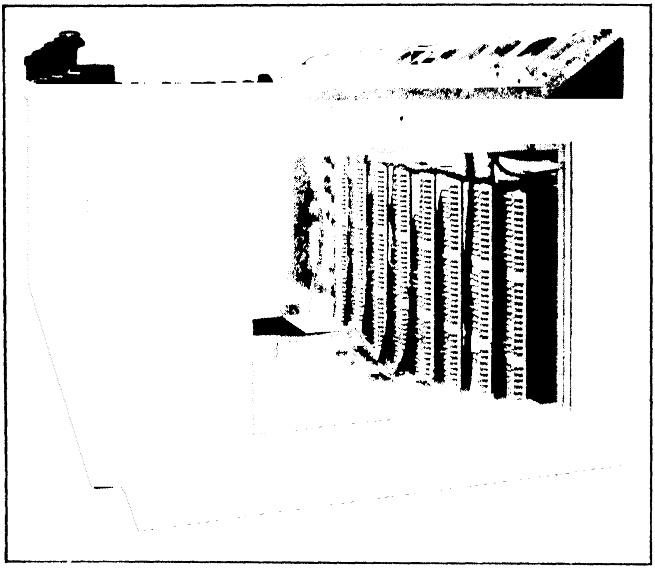


FIG. 221. Side view of control desk showing arrangement of wiring and terminal boards.

In laying out devices on the top of a desk, care should be taken to obtain a neat, orderly, and logical arrangement, as this increases materially the efficiency of the operator. Attention should also be given to the wiring inside the desk. All wiring should be firmly supported and terminated at terminal boards, indelibly marked with cir-

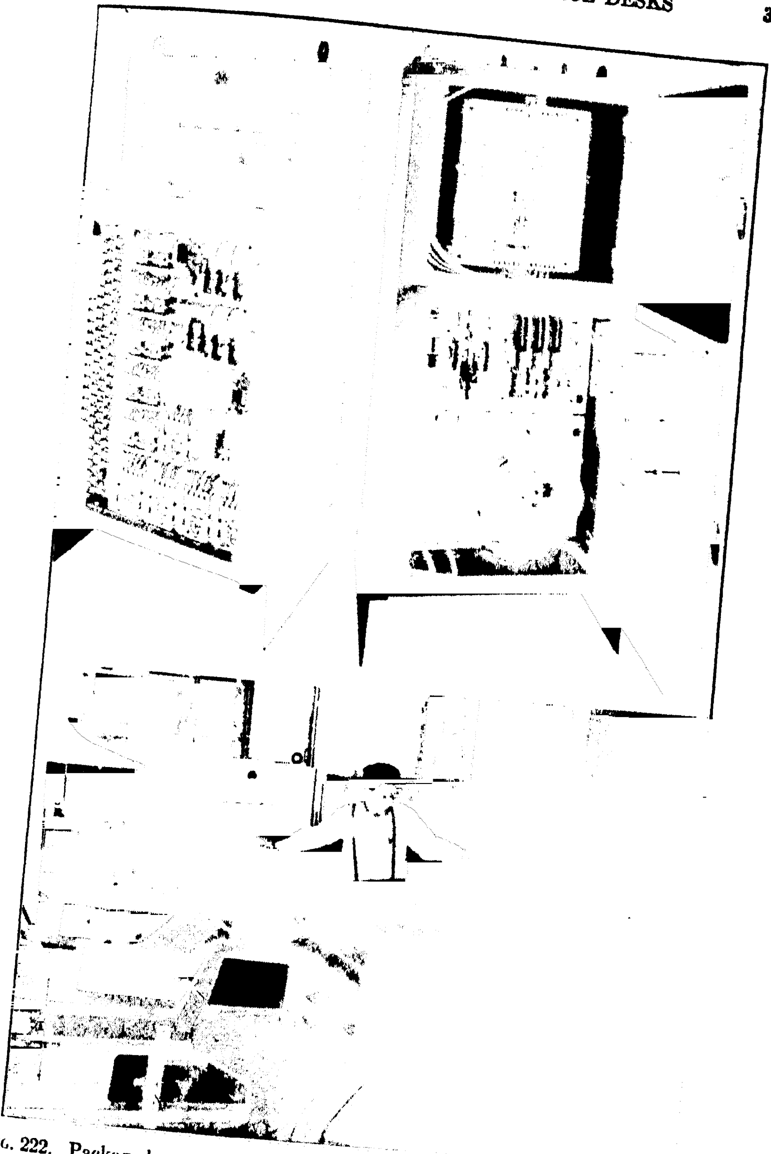


Fig. 222. Packaged control unit for paper bag machine. *Upper left.* Front view. *Upper right.* Back view. *Bottom.* Installation view.

cuit numbers in accordance with the connection diagram, and easily accessible from the front or the side. As most electricians are right handed, it is easier for them to make connections to terminal boards if they are in the right-hand side of the desk. The wiring to the terminal boards should be kept back of the boards as far as possible. Figure 221 is the side view of a control desk. The terminal boards are mounted on straps in the back. The control wiring is cabled and laced, and laid partly in wiring troughs. The interior is kept unobstructed, giving the electrician a maximum amount of working space.

Packaged Control Units [8]

On equipments which use small magnetic devices, it is possible to combine the operator's panel, with its pilot devices, and the magnetic control panel into a single packaged control unit. Such a combination is feasible only for drives involving comparatively small motors, as otherwise the size of the contactor panel would exceed the space available for an operator's panel. A consolidation, when possible, offers the advantage that a completely wired unit is delivered from the factory to the site of the installation, and the user has only to prepare the foundation, set the unit in place, and make the outgoing connections.

Figure 222 is an installation view and a close-up of a packaged control unit for a machine making paper bags. On the front of the top portion are mounted control switches and push buttons required by the attendant to operate the several motions of the machines. The front compartment contains the panel for the magnetic control of the paster and cutter motors, and the rear compartment houses the main drive and electronic register control. This arrangement reduces the number of control units that must be handled at the installation and combines all control elements into a single compact unit, reducing installation expense and saving space.

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CHAPTER 11

BASIC DIRECT-CURRENT CONTROL CIRCUITS

In the following three chapters are discussed basic circuit elements forming the building blocks of which complete standard or special magnetic controllers are constructed. In presenting these elementary circuits, no attempt is made to present actual controllers in all details. Only those details are given in the diagrams which illustrate the essential elements of each basic circuit. How these basic circuits are used on practical controllers is explained in subsequent chapters.

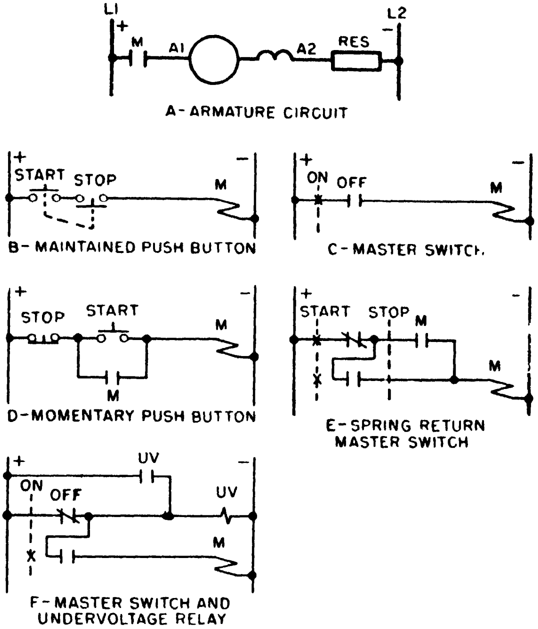
Starting

The term *starting* designates the function of connecting the motor to the line so that current may flow through its armature. In a d-c shunt motor it is assumed that the shunt field has been energized previously. In a d-c series motor the series field is energized simultaneously with the armature. In Fig. 223 sketch *A* is the power circuit of the motor armature. When line contactor *M* closes, current flows through the motor armature, the motor develops torque and starts rotating. To limit the current at the instant at which *M* closes to a safe value which the motor can commutate, a block of resistance is connected in series with the motor armature. Very small motors, fractionals and integrals up to about 2 hp, often have a sufficiently high internal resistance so that external resistance can be omitted.

The simplest method of closing contactor *M* is by a maintaining type push button station, as shown in sketch *B*. When the start button is pressed, the coil of contactor *M* is energized and *M* closes. When the stop button is pressed, the coil of *M* is de-energized, and the contactor drops out. In place of the push button station, a master switch with maintained contact, illustrated in sketch *C*, may be used. Turning the master switch to the on position energizes contactor *M*. Turning the master switch to the off position de-energizes *M*. Any maintained contact type pilot device, such as a float switch, pressure switch, or thermostat, may be used in place of the master switch. Contactor *M* stays closed as long as the pilot device stays closed.

The above methods of controlling contactor *M* provide *under-voltage release*. If control voltage disappears, or the control circuit is interrupted by other means, contactor *M* is dropped out. When control voltage is re-established, *M* recloses immediately and stays closed as long as the pilot device remains closed.

Such automatic restarting is required in many cases, especially where automatic machinery such as pumps, compressors, and blowers operate without attendance. Safety considerations for operating personnel, however, require that attended production machinery must not restart automatically once the motor has been stopped, making it necessary for the operator to close a pilot device. It is called *undervoltage protection.*



A-ARMATURE CIRCUIT

B-MAINTAINED PUSH BUTTON

C-MASTER SWITCH

D-MOMENTARY PUSH BUTTON

E-SPRING RETURN MASTER SWITCH

F-MASTER SWITCH AND UNDERVOLTAGE RELAY

FIG. 223. D-c motor-starting circuits. *M*. Line contactor. *UV*. Undervoltage relay.

Undervoltage protection is an inherent feature of momentary contact push button control. See sketch *D*. When the start button is pressed, contactor *M* closes. A normally open interlock on *M* establishes a sealing circuit around the start button, which is then released, and contactor *M* stays closed. To open *M*, the stop button is pressed momentarily. This de-energizes *M*. When the stop button is released, *M* does not reclose, until the start button is pressed again. Several start buttons may be connected in parallel and several stop buttons may be connected in series so that the motor can be started and stopped from several remote-control points. If control voltage disappears while the motor is running, contactor *M* drops out. When control voltage reappears, contactor *M* does not close immediately; it is necessary to press the start button again before the motor starts.

Spring return master switches also provide undervoltage protection inherently. See sketch *E*. The master switch is arranged so that a spring turns the switch back to the neutral position, when its handle is released. Turning the master switch to start energizes *M*, and a normally open interlock on *M* closes a sealing circuit, holding *M* energized when the master switch returns to neutral. When the master switch is turned to stop, *M* drops out, but does not reclose when the master switch returns to neutral. When *M* is dropped out because of loss of control voltage, the master switch must be turned to start again before *M* recloses.

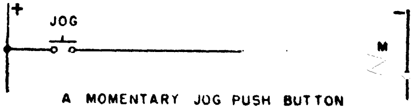
When a master switch with maintained contacts is used, a separate undervoltage relay is provided for protection, as is indicated in sketch *F*. Undervoltage relay *UV* is energized through a master switch contact which is closed only in the off position. As long as control voltage is available, relay *UV* stays energized through its own normally open holding interlock, regardless of the position to which the master switch is turned. Contactor *M* closes and opens when the master switch is manipulated between the on and off positions. When control voltage disappears while the motor is running, that is, with the master switch in the on position, relay *UV* and contactor *M* drop out. Upon re-establishment of control voltage, the master switch must be returned to the off position, in order to reclose *UV* before the motor can be started again.

Jogging

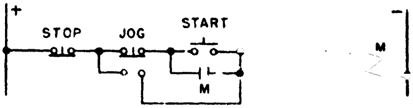
Jogging or *inching* is defined by NEMA as the quickly repeated closure of the circuit to start a motor from rest for the purpose of accomplishing small movements of the driven machine. This means that the motor does not run for any length of time, but only for a short interval, as controlled by the operator. Jogging is frequently used on production machinery, for instance, to bring the tool of a machine tool into alignment with the work or to thread cloth into a printing machine.

Several jogging control circuits are indicated in Fig. 224. The simplest jogging control is obtained by a single momentary contact push button as shown in sketch *A*. Contactor *M* is energized and the motor turns only as long as the push button is held depressed. This control circuit is satisfactory for intermittent drives which travel for only a short distance. In the majority of cases it is desired to jog the machine, and then to start it for a long-time run.

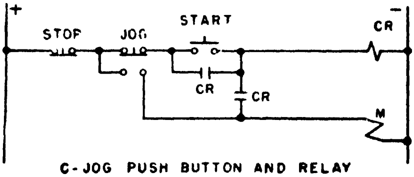
See sketch *B*. A jog button is provided in addition to the regular start and stop buttons. When the jog button is pressed, the normally closed back contact interrupts the sealing circuit through the interlock on *M;* thus *M* drops out as soon as the jog button is released. This method has a serious disadvantage. If the jog button is released suddenly, its normally closed back contact may close before contactor *M* has dropped out. If this happens, the sealing circuit is re-established and the motor continues to run, constituting a danger to the operator, who may be intent on inching his work and who might be hurt by the unexpected starting of his machine. Jogging push buttons can be equipped with a latch which prevents the normally closed back contact from reclosing as long as the latch is turned.



A MOMENTARY JOG PUSH BUTTON



B-SEPARATE JOG PUSH BUTTON



C-JOG PUSH BUTTON AND RELAY

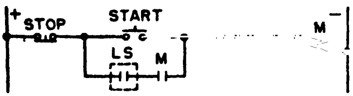
FIG. 224. Jogging control circuits. *M*. Line contactor. *CR*. Control relay.

A safer method of jogging is obtained by the circuit of sketch *C*. A control relay *CR* is added. When the start button is pressed, relay *CR* is energized, which in turn energizes contactor *M* and provides the sealing circuit. When the jog button is pressed, contactor *M* is energized directly and relay *CR* is not in the circuit. With this connection, relay *CR* is positively prevented from closing when the normally closed back contact of the jog button recloses, and there is no danger of contactor *M* staying energized. Although the circuit according to sketch *C* involves the expense of an additional relay, it offers the highest degree of safety to the operator.

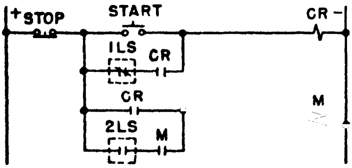
Limit Switch Cycling

Cycling or *indexing* means that the motor is started and runs for a predetermined distance of the driven machine, and then stops automatically. The cycle is repeated as often as the operator desires. An example is a rotary car dumper which starts, rotates through a complete revolution, and then stops automatically. Such cycling can be controlled by limit switches, and several circuits which accomplish this are shown in Fig. 225.

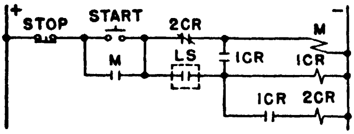
See sketch *A*. Limit switch *LS* is actuated by the driven machinery. In the index position, *LS* is open. When the operator presses the start button, contactor *M* closes and the motor starts. The operator must keep the start button depressed for a certain length of machine travel until the limit switch recloses. When the push button is then released, contactor *M* is held closed through *LS* and its own holding interlock. When the index position is reached, *LS* opens, drops out *M*, and stops the motor. This circuit has the advantage of simplicity. Its disadvantage is that, when a new cycle is started, the start button must be held depressed for a certain length of time, requiring judgment on the part of the operator. On slow-moving drives, a considerable period of time may elapse before *LS* recloses, during which the operator must hold the start button closed.



A-SINGLE LIMIT SWITCH



B-TWO LIMIT SWITCHES AND RELAY



C-ONE LIMIT SWITCH AND RELAY

Fig. 225. Control circuits for limit switch cycling. *M*. Line contactor. *CR*, 1*CR*, 2*CR*. Control relays. *LS*, 1*LS*, 2*LS*. Limit switches.

This is avoided by the circuit of sketch *B*. Two limit switches are provided, 1*LS* and 2*LS*. In the index position, 1*LS* is closed and 2*LS* is open. When the start button is pressed, relay *CR* is energized, seals itself in through 1*LS*, and energizes contactor *M*. Shortly after the drive has started, limit switch 2*LS* recloses and establishes a sealing circuit for *M*. A short distance beyond this point, limit switch 1*LS* opens and causes relay *CR* to drop out. A short distance before the index point is reached again, 1*LS* recloses, but no change takes place in the control circuit. When the index point is reached, 2*LS* opens and drops out *M*, thus stopping the motor. Pressing the start button again restarts the cycle.

The circuit in accordance with sketch *C* eliminates the necessity of using two limit switches. One limit switch *LS* is required, which opens at the index point. Pressing the start button energizes contactor *M* through the normally closed contact of relay 2*CR*. Contactor *M* seals itself in. After the drive has traveled a short distance, *LS* recloses and energizes relay 1*CR* which seals in contactor *M* through *LS*. Relay 1*CR* in turn energizes relay 2*CR*, which opens its contact and thus places *M* under the control of *LS*. At the index point *LS* opens, drops out 1*CR* and *M*, and stops the motor. Relay 2*CR* drops out and recloses its contact. Pressing the start button restarts the cycle. It would be possible to eliminate relay 2*CR* by using a normally closed contact on 1*CR*, so adjusted that it opens after the normally open contacts on 1*CR* close. However, as such an adjustment is difficult to maintain, the use of a separate relay 2*CR* is preferred.

With any one of the control circuits shown, it is possible to intercept the cycle and stop the motor by pressing the stop button. The cycle can be completed by pressing the start button again.

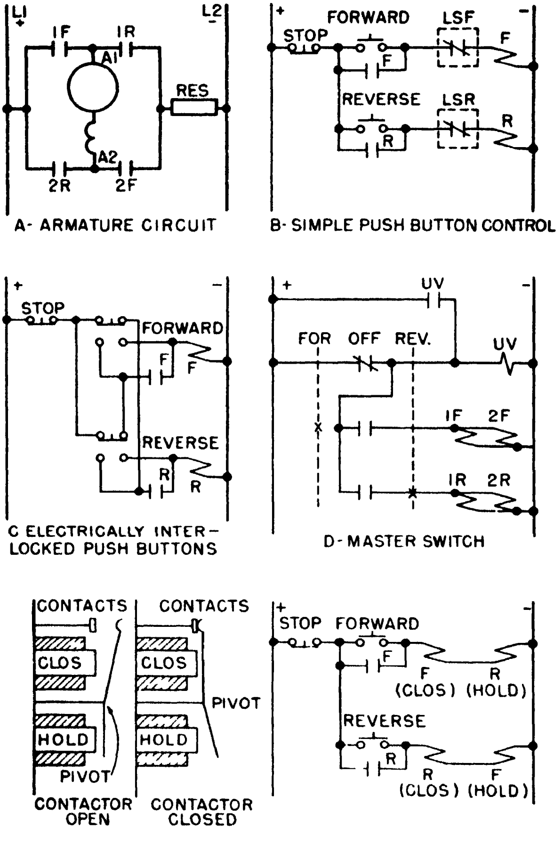
Reversing

To reverse the direction of rotation of a d-c motor it is necessary to reverse the direction of current flow through either the armature or the field circuit. Let us consider first control circuits used to reverse the armature.

See Fig. 226. Sketch *A* indicates the armature circuit. With small motors, double-pole contactor *F* for the forward and *R* for the reverse direction are used. On controllers for larger motors, single-pole contactors 1*F*, 2*F* close for forward rotation, that is, current flow through the armature from *A*1 to *A*2, and contactors 1*R*, 2*R* close for reverse rotation, that is, current flow through the armature from *A*2 to *A*1. Except for very small motors, a resistor must be connected in series with the armature to reduce the starting current to a value within the commutating limit of the motor.

Provision must be made to prevent the forward and reverse contactors from being closed at the same time. Mechanical interlocks of a type shown in Fig. 102 are used between reversing contactors wherever possible. When single-pole contactors are used, mechanical interlocks are arranged between 1*F*–1*R* and 2*F*–2*R*. No current would flow if 1*F* and 2*R* or 2*F* and 1*R* were closed at the same time.

Mechanical interlocks safeguard against two contingencies. One is inadvertent energizing of the coils of both the forward and reverse contactors. Assume that the forward contactors are energized. When the coil of the reverse contactors are then also energized, their air gap is large and the resultant magnet pull is less than the pull which holds the forward contactors closed. The mechanical interlocks prevent the reverse contactors from closing as long as the forward contactor coils are energized. Since d-c contactors are usually equipped with continuously rated coils, and since the coil current depends solely on coil resistance, it is not necessary on d-c controllers to interlock reversing contactors electrically. This is an important difference



A- ARMATURE CIRCUIT

B- SIMPLE PUSH BUTTON CONTROL

C ELECTRICALLY INTER-LOCKED PUSH BUTTONS

D- MASTER SWITCH

E- INTERLOCKING THROUGH HOLDING COILS

FIG. 226. Control circuits for armature reversing. *F*, 1*F*, 2*F*. Forward contactors. *R*, 1*R*, 2*R*. Reverse contactors. *UV*. Undervoltage relay. *LSF*. Forward limit switch. *LSR*. Reverse limit switch.

between d-c and a-c reversing controllers, discussed in greater detail in the next chapter.

Another contingency is the case where one set of reversing contactors freezes in, that is, the contact tips weld closed and the contactors do not open when their coils are de-energized. Assume that one or both forward contactors are frozen and their coils are de-energized. When the reverse contactors are then energized, either one of two things may happen. If the contacts of the forward contactors are welded only lightly, the pull exerted by the mechanical interlocks in addition to the pressure of the contact springs may be sufficient to pry the forward contactors open, and then the reverse contactors may close. Or, if the forward contactors are frozen tight, they stay closed and the reverse contactors are prevented from closing.

A simple reversing control circuit with momentary contact push buttons is illustrated in sketch *B*. For the sake of simplicity it is assumed that only one double-pole forward contactor *F* and one double-pole reverse contactor *R* are used. When the forward push button is pressed, contactor *F* is energized and seals itself in. If the reverse push button is then pressed the coil of contactor *R* is energized, which does not close on account of the mechanical interlock. Before the motor can be reversed, it is necessary to press the stop button, which drops out the contactor *F* so that *R* can be closed by pressing the reverse button. If overtravel limit switches are used on intermittent reversing drives, they are connected in series with the contactor coils. For instance, if the motor runs forward and the end of the travel is reached, limit switch *LSF* opens, drops out *F*, and stops the motor. The forward push button is then ineffective, and no further forward travel is possible.

Push button control provides undervoltage protection inherently. Upon loss of voltage, either *F* or *R*, whichever happens to be closed, drops out. Upon reappearance of control voltage, it is necessary to press either the forward or reverse push button to restart the motor.

When push buttons with normally closed back contacts are used, the push buttons can be electrically interlocked, as indicated in sketch *C*. The forward button circuit is carried through the back contact of the reverse button and vice versa. If contactor *F* is energized and the reverse button is pressed, its back contact opens the coil circuit of *F* and permits *R* to close. While such electrical interlocking is not a necessity, it is often included as an additional safeguard without extra expense, when heavy-duty push buttons are used on which back contacts are available.

Sketch *D* shows a reversing control circuit employing a master switch. For purpose of illustration, single-pole contactors 1*F*, 2*F* and 1*R*, 2*R* are indicated. Coils of each pair of reversers are connected in parallel. As a master switch is generally a maintained contact device, an undervoltage relay *UV* is required for undervoltage protection. Upon loss of control voltage, the master switch must be returned to the off position, before *UV* and either set of reversers can be energized again.

On small contactors, as shown in Fig. 100, it is impractical to arrange for reliable mechanical interlocks, especially when the contactors operate frequently and interlocks would be subject to considerable wear. Holding coils are then used in lieu of mechanical interlocks (see sketch *E*). A contactor with holding coil has two magnet cores. When the contactor is open and both the holding and the closing coil are energized simultaneously, the holding coil pull is stronger than the closing coil pull, and the contactor stays open. Conversely, if the contactor is closed and the holding coil is then energized, the contactor stays closed as the closing coil pull exceeds the holding coil pull. To illustrate the holding coil function, assume that the forward button is pressed. Contactor *F* closes. The holding coil of *R* is also energized. If the reverse button is then pressed, *F* stays closed and *R* does not close. The holding coils act exactly like mechanical interlocks. It must be recognized, however, that holding coils do not protect against closing of both reversers in case one contactor freezes in, as mechanical interlocks do.

Control of Shunt Field Circuits

The majority of d-c motors used in industry are shunt motors. In addition to the control of the armature circuit, the connections of the field circuit must be given consideration.

Figure 227 is the elementary diagram of a simple push-button-operated starting circuit for a shunt motor. The control circuit is connected across the power line and the shunt field is connected in parallel with the armature circuit on the load side of line contactor *M*. When the motor is stopped, by opening *M*, the shunt field is disconnected from the line. The field circuit is not interrupted, as the armature circuit provides a discharge path and no dangerous rise of voltage across the shunt field terminals occurs. This connection is used widely for small continuously operating motors. The circuit is simple, and when the motor is shut down the field winding is disconnected and does not heat. As the field current rises gradually from zero to normal value when *M* closes, the starting torque also rises gradually from zero to its normal value. It is not important when motors are infrequently started, and the slight increase in starting time is of no consequence.

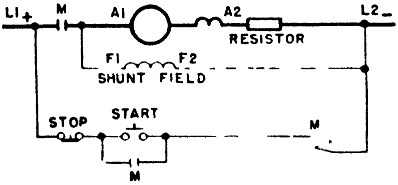
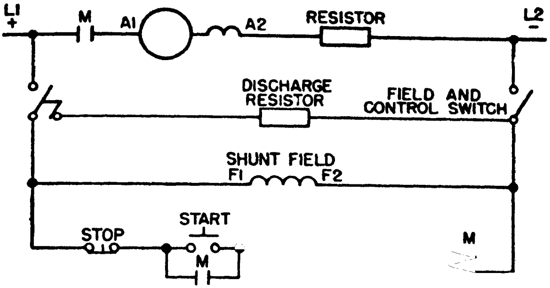
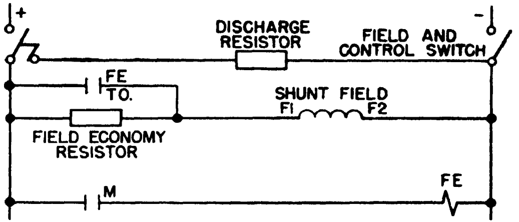


FIG. 227. Complete starting circuit for d-c shunt motor. *M*. Line contactor.

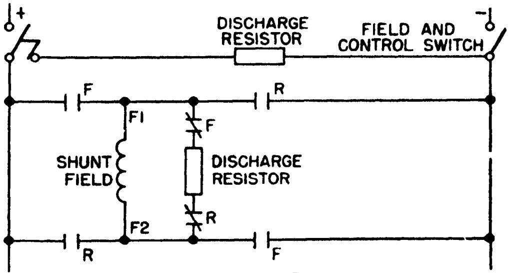
On intermittent drives, requiring frequent starts, this delay in build-up of starting torque is often objectionable. To have high starting torque available when the motor is energized, it is necessary to maintain full, or at least partial, field strength while the motor is



A-PERMANENTLY CONNECTED SHUNT FIELD



B-USE OF FIELD ECONOMY RESISTOR



C - FIELD REVERSING CIRCUIT

Fig. 228. D-c motor shunt field control circuits. *M*. Line contactor. *F*. Forward contactor. *R*. Reverse contactor. *FE*. Field economy relay.

shut down. In Fig. 228 several field control circuits are shown which are suitable for use on intermittent-duty drives.

In sketch *A* the field circuit is permanently connected to the power line, and the field is kept fully excited at all times. Naturally, the field is subjected to full heating while the motor is standing still and the cooling effect of the rotating armature is lacking. This heating must be considered in the design of the field structure. During a prolonged shut-down period of the motor, it is desirable to disconnect the field in order to reduce its heating. A field and control switch is usually included in the controller to disconnect the shunt field from the line. To avoid excessive build-up of voltage when the field circuit is interrupted, the field switch is equipped with discharge clips, and a discharge resistor is connected in parallel with the field when the field switch is opened.

Some intermittent-duty drives, for instance mine hoists, operate on regular duty cycles with only short stops between cycles. But it may happen that operations are delayed, and occasionally a longer standstill period occurs between cycles. To reduce the heating of the field during such standstill periods, a field economy resistor may be inserted in series with the field, as shown in sketch *B*. It is customary to use a resistor which reduces the field current to 1/1.41 of its normal value, thus reducing the heating to one half of normal.

While the motor runs, the field economy resistor is short-circuited by the contacts of field economy relay *FE*. The coil of this relay is energized by a normally open interlock of line contactor *M*. Thus the contact of *FE* is closed as long as *M* is closed. Relay *FE* is of the time delay drop-out type. When *M* is open during a short stop of the motor, *FE* does not drop out, and normal field strength is maintained. When *M* is open for a longer time than the setting of *FE*, the relay drops out and inserts the economy resistor in series with the field.

Large motors that are infrequently started are sometimes reversed by reversing the shunt field rather than the armature. Smaller contactors can be used in the field circuit, reducing cost and size of the controller. See sketch *C*. To avoid an excessive voltage rise when the reversing contactors open, these contactors are equipped with normally closed contacts which connect a discharge resistor in parallel with the shunt field when the reversers open. The circuit of sketch *C* is used not only to reverse motor shunt fields but also in generator field circuits of adjustable-voltage systems to reverse the motor by reversing the polarity of the generator.

Armature Acceleration

So far it has simply been assumed that a block of resistance is connected in the motor armature circuit to limit the current at the instant the motor is connected to the line. In Chapter 2 it is shown that a resistor, permanently connected in series with the motor armature, affects the speed-torque characteristic and prevents the motor from attaining full speed at full load. To permit the motor to accelerate to full speed, the resistance in series with the armature, called the starting resistance, must ultimately be short-circuited so that the motor is connected across the line. As current (or torque) peaks during acceleration must be limited to a value commensurate with the commutating ability of the motor, or with torque limitations of the driven machinery, the starting resistor may have to be short-circuited in several steps. For an explanation of d-c motor acceleration by short-circuiting its armature starting resistor, see Fig. 229.

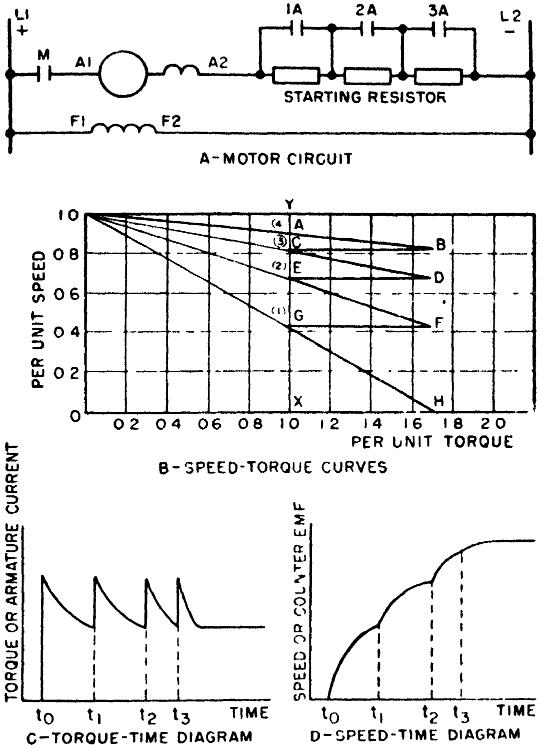


FIG. 229. Acceleration of a d-c shunt motor. *M*. Line contactor. *1A*, *2A*, *3A*. Accelerating contactors.

Sketch *A* is the elementary diagram of a shunt motor starting circuit with three steps of starting resistance and three accelerating contactors. Such a starter is called a four-step or four-point starter. On the first step line contactor *M* closes and the motor armature is connected to the line with all starting resistance in series. On steps 2, 3, and 4 accelerating contactors 1*A*, 2*A*, 3*A* close in sequence with intervals between steps, as governed by the characteristics of the control system chosen for the starter. When all accelerating resistance is short-circuited, the motor is connected across the line and accelerates to its full running speed. Commercial starters are designated by the number of steps or points they provide, which is one more than the number of accelerating contactors used.

The total amount of starting resistance is governed by the desired starting torque, which in turn must be selected by the application engineer to suit the driven machinery. See the resistor classification table in Chapter 9 for starting torques recommended for commonly used types of machinery. In sketch *B* speed-torque curves are plotted for a starter in accordance with sketch *A*. The speed-torque curve for each step is a straight line, and the point at which it intersects the unity torque line is determined by the amount of resistance in series with the motor on that step. The heavy lines indicate how the motor accelerates, assuming that the load torque of the drive is constant over the whole range from zero to full speed. Furthermore, the resistor has been designed so that the torque peaks during acceleration are equal to the starting torque.

When line contactor *M* closes, the motor develops a starting torque equal to *OH*. In the per unit system *OX* is the full-load torque and *XY* is base resistance, defined as line voltage divided by full-load current. In other words, unity resistance is the total resistance of the armature circuit (internal plus external) which would obtain unity starting torque. In per unit, *YA* is the internal resistance of the motor, *AG* the total external starting resistance, and *YG* the total resistance. Expressed in per unit, the starting torque is

$$T_{\text{starting}} = OH = \frac{1}{YG} \qquad (67) \blacksquare$$

As the starting torque exceeds the load torque, the motor gains in speed. During acceleration the torque decreases. The motor accelerates along speed-torque curve *HG* until the motor torque becomes equal to the load torque. At this point motor speed in per unit is *XG*. As motor armature current is proportional to motor torque, field current and flux being constant, the decrease in motor torque corresponds to a decrease in armature current, which in turn results in a decrease in drop across the starting resistor. Correspondingly the counter emf of the motor and its speed increase. Expressed in per unit, *OH* is the starting current and *OX* is the full-load current. Likewise *XY* is the line voltage and *XG* the counter emf of the motor

Sketch C indicates in a general manner how torque and armature current vary as a function of time. At time t_0, the line contactor closes and the starting torque is developed instantly. At time t_1 the torque has decreased to the full-load value. The exact shape of the torque-time curve varies with mechanical characteristics of the drive, such as friction and inertia, and the sketch intends only to illustrate the general shape of the curve. Correspondingly, sketch D shows how the motor speed increases during time interval $t_0 - t_1$.

When equilibrium between motor torque and load torque has practically been reached at time t_1, the first accelerating contactor $1A$ is closed, short-circuiting the first step of starting resistance, which in per unit is equal to EG. As the motor counter emf and speed cannot change instantly, current and motor torque must rise to such a value that the drop through the remaining sections of external resistance and internal resistance equals YG. Thus the armature current and torque suddenly increase to point F, along line GF. As the torque then exceeds the load torque, the motor accelerates along line FE. The torque decreases and the speed increases, until at time t_2 the motor torque practically equals the load torque at point E in sketch B.

Accelerating contactor $2A$ then closes. The torque rises instantly to point D. The motor accelerates along line DC until at point C motor torque equals load torque at time t_3. When the last accelerating contactor $3A$ is closed and the remaining section of starting resistance is short-circuited, the motor is connected across the line. The torque rises to point B, and the motor accelerates to point A, which is its natural full-load speed. The motor is then fully accelerated.

The starting resistance required for a given application is most conveniently determined by a graphical method, as illustrated by sketch B. It should be kept in mind that commercial resistors may deviate plus or minus 10 per cent from their nominal resistance. It is futile to calculate a starting resistor by time-consuming analytical methods which yield very accurate results on paper but cannot be realized in practice because of inherent variations in resistance of practical resistors.

For a resistor lay-out, proceed as follows. Determine the desired starting torque from application data, so that point H is established and line (1) can be drawn. The intersection with the unity torque line yields point G. Draw a horizontal line through point G and make GF equal to XH. Then draw line (2), which fixes point E. Draw a horizontal line through point E and make ED equal to XH. Line (3) can then be drawn and point C established. Draw a horizontal line through *C* which intersects the fundamental speed-torque curve in point *B*. When *CB* is equal to or smaller than *XH*, the accelerating peaks do not exceed the starting torque. If it is found that *CB* is larger than *XH*, either the torque peaks must be somewhat increased or an additional step of starting resistance must be used After the speed-torque diagram has been established, the intersections of the speed-torque lines with the unity torque line give the per unit values of the starting resistance sections. *EG* is the first or 1*A* section, *CE* is the second or 2*A* section, and *AC* is the third or 3*A* section.

In a similar manner, the starting resistance for series or compound wound motors can be determined graphically. As the motor speed-torque curves are not straight lines, it is advisable to use such a chart as is shown in Fig. 18 for preliminary resistor lay-outs. When a high degree of accuracy is required for a specific motor application, the preliminary resistor lay-out must be checked against speed-torque curves calculated for the motor in question.

Control of Acceleration

Control of acceleration comprises the means for controlling the closing of the accelerating contactors in proper sequence, after the line contactor has closed. To obtain smooth acceleration, the accelerating contactors should close when the motor has accelerated on the preceding steps to such a speed that the contactor closing will not cause the torque to exceed the predetermined torque peak. As shown in Fig. 229, the accelerating contactors should close at or a little after the time intervals t_1, t_2, t_3. The following methods are in common use to control accelerating contactor closing.

1. *Current limit control.* As the motor accelerates on each step, the current drops from a peak value to a lower value. The reduction of the current to a predetermined value can thus be made a criterion for closing the next accelerating contactor.

2. *Counter emf control.* While the motor accelerates on each step, the speed and counter emf rise. By measuring the voltage across the motor armature it is possible to determine the speed at which each accelerating contactor should close.

3. *Definite time control.* The most reliable method is obtained by introducing a definite time interval between the closing of successive accelerating contactors and by adjusting the timing so as to obtain uniform accelerating-current peaks.

In the following paragraphs the basic circuits of starters using the above accelerating control methods are described. The elementary diagrams show only such circuit elements as are necessary to bring the salient features of the basic control circuits. Actual control- incorporate additional elements, especially protection. Practical ontrollers are explained in detail in Chapters 17, 18, 19.

Figure 230 is the basic diagram of a current limit type starter. Accelerating relays 1*AR*, 2*AR*, 3*AR* respond to the motor armature current. These relays have a light-weight armature so that they pick up and open their contact very fast when a current higher than normal motor current flows through their coil. When the current drops to a set value, the relays drop out and close their contacts.

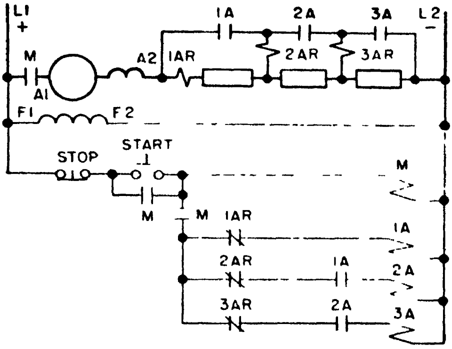
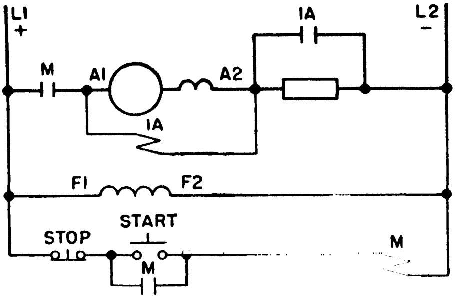


FIG. 230 Starting control circuits with current limit acceleration. *M*. Line contactor. 1*A*, 2*A*, 3*A*. Accelerating contactors. 1*AR*, 2*AR*, 3*AR*. Accelerating relays.

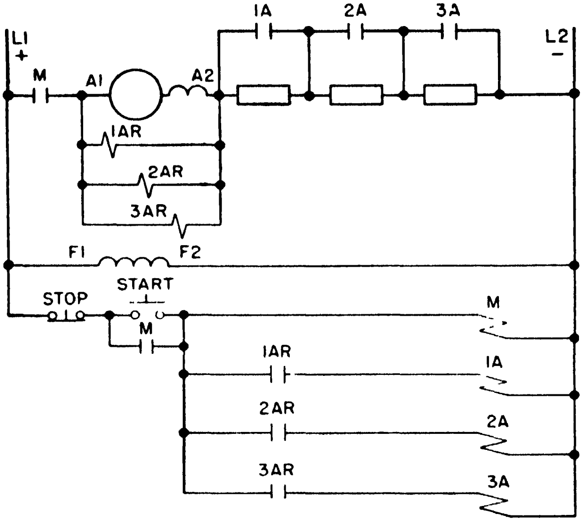
Pressing the start push button energizes line contactor *M*, which seals itself in through a normally open interlock. Another interlock on *M* prepares a circuit to energize the accelerating contactors. However, before contactor coil 1*A* is energized through interlock *M*, accelerating relay 1*AR* has opened its contact, thus preventing 1*A* from closing. It is essential that relay 1*AR* open very fast and that the interlocks on *M* close a sufficient time after the main contact of *M* has closed to enable 1*AR* to open in the meantime.

When the armature current drops to normal, relay 1*AR* drops out and closes its contact, energizing contactor 1*A*, which closes. Current then flows through relay coil 2*AR*, and this relay opens its contact. An instant later an interlock on 1*A* closes and prepares a circuit for coil 2*A*. The armature current drops to normal as the motor accelerates further, and relay 2*AR* drops out and closes its contact. Contactor coil 2*A* is then energized, and contactor 2*A* closes. Current flows through the coil of relay 3*AR*, which picks up and opens its contact. An instant later, an interlock on 2*A* closes and prepares a circuit for coil 3*A*. As the motor armature current decreases, relay

3AR closes its contact and causes contactor *3A* to close. The motor is then connected across the line and the accelerating cycle is complete.



A-WITH CONTACTOR ACROSS ARMATURE



B-WITH SEPARATE VOLTAGE RELAYS

FIG. 231. Starting control circuit with counter emf acceleration. *M*. Line contactor. *1A, 2A, 3A*. Accelerating contactors. *1AR, 2AR, 3AR*. Accelerating relays.

To insure successful operation of this type of starter, the current limit relays must be light and fast. The adjustment of electrical interlocks on the contactors must be maintained carefully so that they close slightly after the main contactor tips close in the power circuit

Figure 231 shows basic circuits of starters with counter emf acceleration. A simple circuit frequently used on small starters with only the accelerating contactor is indicated in sketch *A*. The coil of accelerating contactor 1*A* is connected in parallel with the motor armature. When line contactor *M* closes, the drop across the motor armature is small and contactor 1*A* stays open until the motor has accelerated to such a speed that the counter emf is sufficiently high to cause 1*A* to close.

Standard contactors do not lend themselves readily to adjustment for pick-up at varying voltages. For this reason, the circuit of sketch *A* is not used when the starter incorporates a number of accelerating contactors which must close at armature voltages varying over a considerable range. In such a case separate voltage relays are connected in parallel with the motor armature, as shown in sketch *B*. Relays are easier to adjust for pick-up at different voltages, and they in turn are used to energize the contactors. When the start push button is pressed, line contactor *M* closes and the motor starts accelerating. When the speed and counter emf have increased to a predetermined value, relay 1*AR* closes, causing contactor 1*A* to close. As the motor speed rises further, relay 2*AR* closes and energizes contactor 2*A*. Finally, as the motor speed rises still further, relay 3*AR* closes and energizes contactor 3*A*, connecting the motor across the line.

Current limit and counter emf methods of starting determine the instant at which accelerating contactors close by measuring some operating quantity of the motor circuit. The contactor closing sequence adjusts itself automatically to varying load conditions and maintains uniform accelerating current and torque peaks. Production machinery may be started light or loaded. When the load is light, the accelerating time is short; when the load is heavy, the accelerating time is longer. However, there is one requirement which must be fulfilled to obtain closing of the accelerating contactors. The motor *must* start on the first step, that is, it must start when the line contactor closes and all starting resistance is in series with the armature. Should the motor fail to start, the armature current will not drop, and the counter emf will not build up. The accelerating contactors will be prevented from closing and the motor will stall, and the starting resistor is in danger of burning out. Even if the motor should start but fail to accelerate to a speed permitting the current limit or counter emf accelerating relays to close, the accelerating contactors will not close.

Many machines operate in widely different ambient temperatures. On a warm summer day, when grease and oil are soft and fluid, the torque required to start the machine is low. On a cold winter morning, especially after a shut-down over the week-end, grease and oil are hard and stiff, friction is high, and a much higher torque is needed to start the machine. If current limit or counter emf acceleration were used, the relays would have to be adjusted so as to obtain starting current peaks sufficient to start the motor under the most adverse condition. These starting peaks would be higher than necessary to start the motor under an average load condition. Thus the current peaks in general would be higher than needed, causing increased maintenance and reducing the life of the motor, particularly if the motor is started frequently.

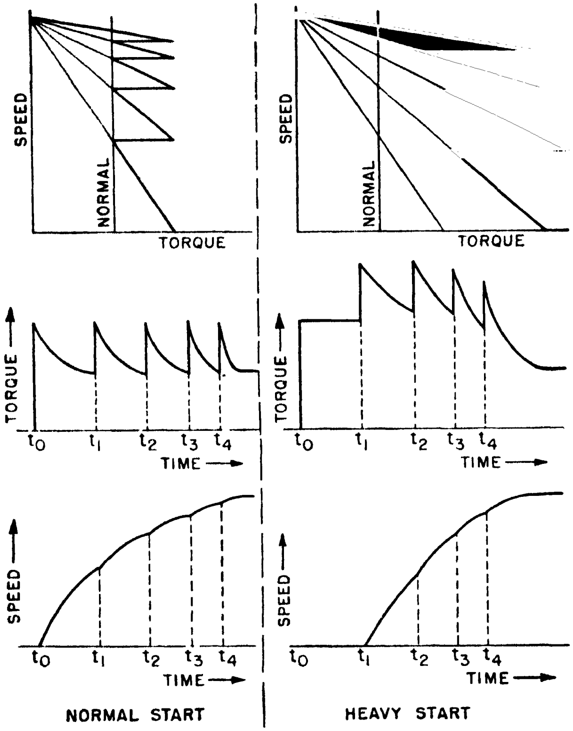


FIG. 232. Comparison between normal and heavy start with definite time acceleration.

This disadvantage is avoided by definite time control of acceleration. With this system, the closing of contactors is made a function of time, and the time intervals between contactors are adjusted so as to obtain smooth acceleration and uniform peaks under average load conditions. If a particularly heavy starting condition occurs and the motor fails to accelerate on the first starter step, the first accelerating contactor closes after a definite time delay, increasing the starting torque. If the motor still fails to start, the second accelerating contactor closes and increases the starting torque still further so that the motor has a chance to break static friction and start the machine. Under such conditions the accelerating current peaks are higher than normal, but they occur only occasionally, whereas on normal starts the peaks are lower. This starting performance is illustrated by Fig. 232. On the left side diagrams are plotted, similar to Fig. 229, for a

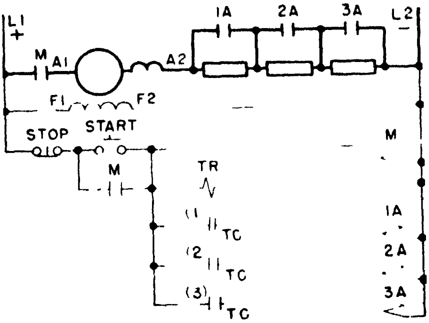


Fig. 233. Starting control circuits with definite time acceleration by mechanical timer. *M*. Line contactor. 1*A*, 2*A*, 3*A* Accelerating contactors. *TR*. Definite time relay.

normal start; on the right side corresponding diagrams are plotted for a heavy start. In both cases the same starter is used with the same resistor layout and the same time intervals between accelerating contactors closing.

Various methods are available to obtain time delay intervals between accelerating contactors. They can be subdivided into three basic types:

1. Mechanical timers.
2. Time delay drop-out contactors.
3. Individual timing relays.

Shown in Fig. 233 is a starter with definite time acceleration by means of a mechanical timer. *TR* is a timing relay, either solenoid or motor-operated. This relay contains a multiplicity of contacts, as many as there are accelerating contactors, which are usually arranged on a common shaft so that they close in time sequence with adjustable time intervals between them.

When the start push button is pressed, line contactor *M* closes and seals itself in. At the same time relay *TR* is energized. After a time delay, contact 1 of the relay closes, which causes contactor 1*A* to close. After another time delay, contact 2 of relay *TR* closes, which energizes contactor 2*A*. After a further time delay, contact 3 of relay *TR* closes, causing contactor 3*A* to close, and the accelerating sequence is completed.

Acceleration by time delay drop-out contactors is illustrated in Fig. 234. An individual contactor is shown in Fig. 111. Each contactor has a normally closed main contact. In other words, the contact is closed when the contactor coil is de-energized, and it opens when the coil is energized. The magnetic structure is designed so that the contactor drops out with a time delay, after its coil has been de-energized. Because of the small travel of its armature it cannot interrupt current, but it can close only under power. It is therefore necessary to energize the accelerating contactors and cause their contacts to open before the motor armature circuit is connected to the line.

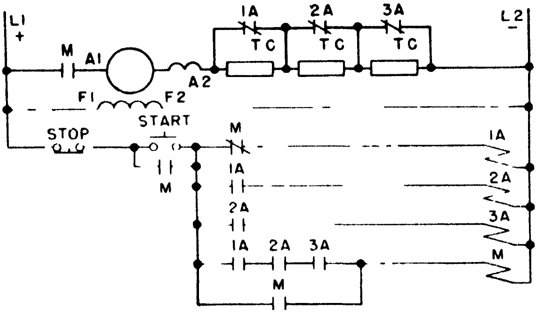


FIG. 234. Starting control circuits with definite time acceleration by time delay drop-out contactors. *M*. Line contactor 1*A*, 2*A*, 3*A*. Accelerating contactors

Pressing the start button energizes contactor 1*A*, which opens its main contact. An interlock on 1*A* energizes 2*A*, and an interlock on 2*A* energizes 3*A*. With all three accelerating contactors open, line contactor *M* closes, as its coil is energized through interlocks on 1*A*, 2*A*, 3*A* in series. Contactor *M* seals itself in. A normally closed interlock on *M* opens and interrupts the coil circuit of 1*A*, which drops out and closes with a time delay. An interlock on 1*A* interrupts the coil circuit of 2*A*, which also drops out with a time delay and closes its main contact. An interlock on 2*A* de-energizes the coil of 3*A*, which also drops out and closes its main contact with a time delay. This completes the accelerating sequence, and the motor is connected across the line.

Time delay drop-out contactors have the advantage that no auxiliary devices, such as timing relays, are required. It must be recognized that such contactors can be used only on starters actuated by push buttons or other single-circuit pilot devices. On many intermittent-duty drives the operator is given manual control over the accelerating contactors so that they can be closed and dropped out at will by moving a master switch to various positions. Standard blowout type contactors are then used which are able to open under current. To avoid too rapid an acceleration when the operator moves the master switch from the off position to one of the running positions, individual definite time delay relays are used to provide the necessary time interval between closing of successive accelerating contactors.

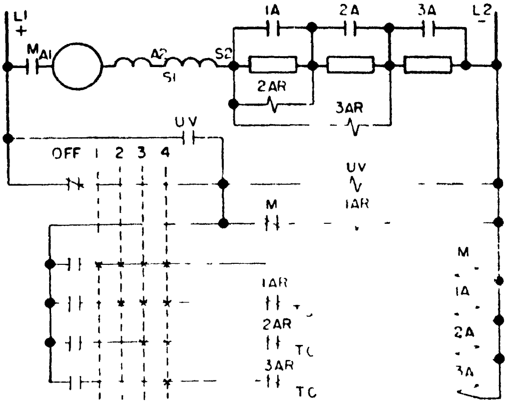


FIG. 235. Starting control circuits with definite time acceleration by definite time accelerating relays. *M*. Line contactor. *UV*. Undervoltage relay. *1A*, *2A*, *3A*. Accelerating contactors. *1AR*, *2AR*, *3AR*. Accelerating relays.

This accelerating system is used widely for intermittent-duty motors. Typical connections for master switch control of a series motor are given in Fig. 235. Undervoltage relay *UV* requires the master switch to be returned to the off position in case of loss of control voltage. When the master switch is moved slowly from the off position through the four running positions, the line contactor and the accelerating contactors close as soon as the respective master switch positions are reached. However, when the master switch is moved rapidly to any position beyond the first, the corresponding accelerating contactors close in a definite time sequence, as governed by the accelerating relays.

Magnetic time delay drop-out relays are used, such as are described in Chapter 4 and shown in Figs. 108, 109, and 110. Relay 1*AR* has a copper-jacketed coil, and it is energized as long as contactor *M* is open. When *M* closes, the coil circuit of 1*AR* is interrupted. 1*AR* drops out with a time delay and closes its contact, which permits contactor 1*A* to close on the second position of the master switch. The coils of relays 2*AR* and 3*AR* are not equipped with copper jackets. Instead they are connected across sections of the starting resistor and obtain their time delay by having their coils short-circuited when contactors 1*A* and 2*A* close. When contactor *M* closes, relays 2*AR* and 3*AR* pick up and open their contacts. When contactor 1*A* closes, the coil of 2*AR* is short-circuited. Relay 2*AR* drops out after a time delay and closes its contact, permitting contactor 2*A* to close on the third master switch position or beyond When 2*A* closes, coil 3*AR* is short-circuited. Relay 3*AR* drops out after a time delay and permits contactor 3*A* to close on the fourth master switch position. The operator may slow down the drive by returning the master switch to the first position, which drops out the accelerating contactors and inserts the starting resistance in series with the motor. When the master switch is then turned rapidly to the fourth position, the motor reaccelerates, and the closing of the accelerating contactors is governed by the time delay provided by the accelerating relays.

Field Acceleration

Speed control of adjustable-speed shunt motors is obtained by means of a rheostat in series with the shunt field. When an adjustable-speed motor is started, the rheostat is preset and the motor accelerates to full speed, as determined by the setting of the rheostat To obtain full starting torque, full field current must be available when the motor is connected to the line. Standard starters for adjustable-speed motors include a full-field contactor or relay which short-circuits the field rheostat, while the motor is accelerated to basic speed by short-circuiting of resistance in series with the armature. After the last accelerating contactor has closed, the full-field contactor or relay opens, and the motor accelerates to full speed, corresponding to the rheostat setting.

When a motor with a wide speed range, say 3 to 1 or 4 to 1, is started and the rheostat is left in a position for maximum speed, the sudden weakening of the field, when the full-field contactor opens, is accompanied by a high armature current peak. This peak current can be limited by a field-accelerating relay. Shown in Fig. 236 are the essential circuits of a definite time acceleration starter which are similar to those of Fig. 234, except that a field rheostat and field-accelerating relay *FA* have been added. Relay *FA* has two coils acting on a common armature, a shunt coil and a series coil. The polarity is such that the flux produced by the two coils during acceleration is in the same direction. When the motor is started, the shunt coil holds the relay closed, and its contact short-circuits the field rheostat. Full field is thus maintained until accelerating contactor 3A drops out and closes. A normally open interlock on 3A disconnects the

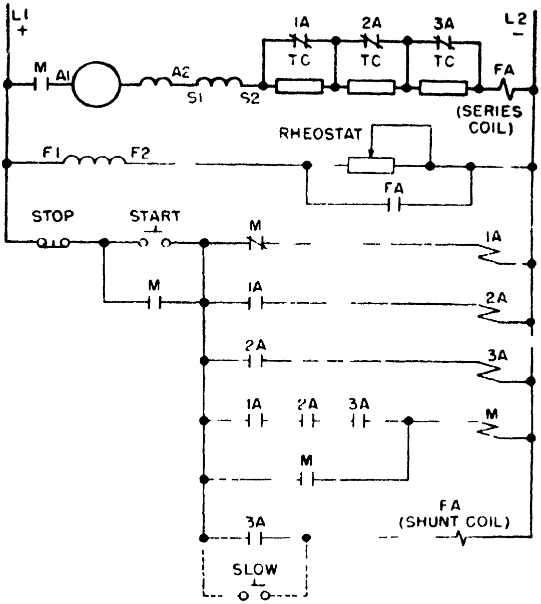


Fig. 236 Starting control circuits for adjustable-speed shunt motor with field accelerating relay. *M*. Line contactor. 1A, 2A, 3A. Accelerating contactors. *FA*. Field accelerating relay.

shunt coil of *FA*, and the relay is then under the control of the current coil. When the motor armature current drops to normal, relay *FA* opens its contact and inserts the rheostat in series with the shunt field. As the armature current rises again, the current coil causes relay *FA* to close. As a result the armature current drops, permitting *FA* to drop out. This cycle may be repeated several times. As the motor speed increases, the current peaks due to dropping out *FA* become smaller and smaller, until finally the motor attains full speed and relay *FA* stays open.

This same relay also acts as a field-decelerating relay. On some applications it is desired to reduce the motor speed temporarily to basic speed, which can be done by connecting a slow push button in the shunt coil circuit of relay *FA*, as indicated by dotted lines. When the slow button is pressed, *FA* is closed by the shunt coil and the field rheostat is short-circuited. The resultant sudden increase in flux causes the motor counter emf to rise suddenly above line voltage and the motor pumps current back into the line, and the direction of armature current reverses. Thus the current coil of relay *FA* bucks the shunt coil. If the reverse decelerating current is sufficiently high, the current coil flux overcomes the shunt coil flux and *FA* drops out, reinserting the rheostat. The armature current then drops, and the shunt coil regains control of *FA*, which closes its contact. This cycle may be repeated several times while the motor decelerates. When basic speed is reached, the current drops to normal and *FA* stays closed.

Relay *FA* is designed with a large air gap in its magnetic circuit Thus the inductance of its coil circuits is low, and flux changes follow changes in series coil current rapidly. The changes in motor armature current during acceleration and deceleration between basic and full speed are contingent upon changes in the flux of the shunt field, which are delayed by the inductance of the field. The armature current peaks do not occur instantly, but the armature current builds up within a short, though finite, time. Thus the fast "telegraphing" action of relay *FA* has the effect of intercepting the build-up of the armature current, and the current peaks are reduced by the relay.

Armature Shunting

In addition to means for starting and accelerating, a controller may have to provide for deceleration of a motor below its full running speed, for instance for the purpose of reducing the kinetic energy stored in the motor and the driven machinery, in order to stop the drive more accurately. Adjustable-speed shunt motors can be slowed down to basic speed by applying full field. Constant-speed shunt motors and series motors can be slowed down by inserting resistance in series with the armature. However, as has been explained in Chapter 2, inserting resistance in series with the armature produces slow-down only when the motor is loaded, but has little effect when the motor is lightly loaded. A reduction of the no-load speed can be obtained by connecting resistance in parallel with the armature, which is indicated in Figs. 20 and 21. With this connection, the motor develops braking torque when the armature shunt is applied while the motor runs at full speed; this torque slows down the motor rapidly.

Shown in Fig. 237 are the principal circuits of a series motor controller with armature shunting. This diagram is similar to Fig. 235 except that a resistor in parallel with the armature is added. The resistor connection is established by contactor *S*. On the first master switch position, *S* is closed and a low no-load speed is obtained. On the second position, *S* is dropped out. On subsequent master switch positions, the accelerating sequence is the same as described for Fig. 235, under the control of definite time-accelerating relays. There is one additional interlocking feature. To avoid excessive current flow through the armature shunt resistor, the closing of the accelerating contactors, which short-circuit the resistance in series with the armature, is prevented as long as *S* is closed. A normally closed interlock on *S* permits contactor 1*A* to close only after *S* has dropped out, so that *S* and 1*A* cannot overlap when the master switch is rapidly advanced from the first position.

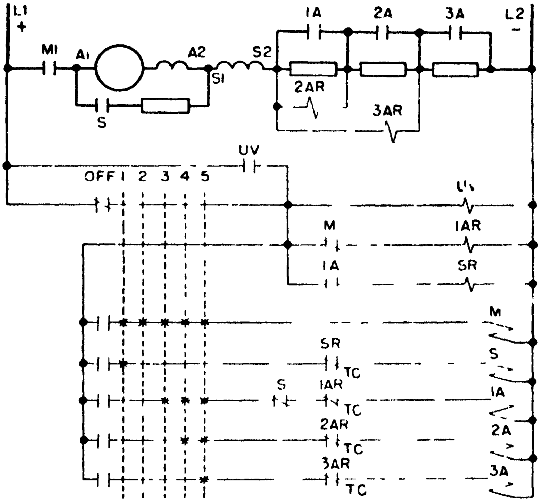


FIG. 237. D-c series motor control circuits with armature shunting. *M*. Line contactor. *S*. Armature shunt contactor. 1*A*, 2*A*, 3*A*. Accelerating contactors. *UV*. Undervoltage relay. *SR*. Armature shunting relay. 1*AR*, 2*AR*, 3*AR*. Accelerating relays.

Another interlocking feature is provided to prevent contactor *S* from closing, upon returning the master switch to the first position, until after the accelerating contactors have dropped out. Otherwise excessive dynamic braking torque peaks would occur. It is prevented by relay *SR*. This relay is energized and opens its contact when accelerating contactor 1*A* closes. When the master switch is returned to the first position, contactor 1*A* drops out and de-energiz the coil of relay *SR*, which drops out and closes its contact with slight time delay. Thus, by delaying the closing of contactor *S* unt after 1*A* has dropped out, assurance is given that the armatur series resistance is inserted before the shunt resistance is connected in parallel with the armature.

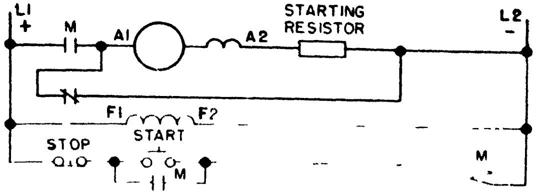
Dynamic Braking

To assist in stopping a motor, or to prevent a motor from being overspeeded by a load under the influence of gravity, a dynamic braking connection may be employed. Such a connection, as has been explained in Chapter 2 (see Figs. 22 and 23), establishes a loop circuit through which armature current can flow. The field of course must stay energized. In a shunt motor, the shunt field remains connected to the line, and in a series motor, the armature loop circuit must include the series field. Shown in Fig. 238 are several basic circuits which are used for dynamic braking. The diagrams include only such details as are required to illustrate the function of dynamic braking control. Only the starting resistor is included, and the details of acceleration control are omitted.

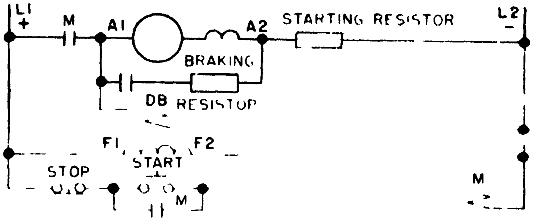
A simple method to obtain dynamic braking of a shunt motor is a normally closed power contact on the line contactor, as is shown in sketch *A*. When the line contactor drops out, this normally closed contact closes and establishes a loop circuit for the motor armature current through the starting resistor. This simple method can be used only on controllers for small motors, since large contactors cannot be obtained with both normally open and normally closed power contacts.

The control circuit of sketch *A* has the advantage that no additional device is required for establishing the dynamic braking loop. The starting resistor is used as a dynamic braking resistor. In the design of the resistor, a compromise must therefore be made between the most desirable starting performance and the most desirable dynamic braking performance. Care must be taken that the accelerating contactors open at the same instant that the line contactor opens. If the dynamic braking circuits were established while the accelerating contactors are still closed, an excessively high armature current would flow, which would damage the commutator.

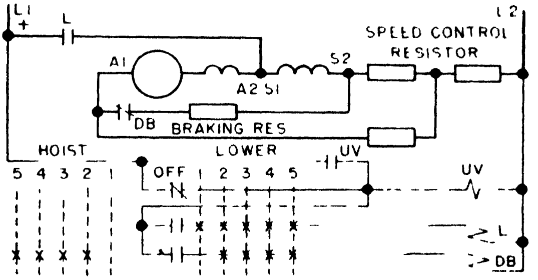
Sketch *B* shows a circuit suitable for use with larger motors. A separate dynamic braking contactor *DB* is used, which establishes the braking loop circuit through a separate braking resistor. This arrangement gives greater flexibility, and the starting and braking resistors can be designed independently for the most desirable starting and braking performance. Also, it is immaterial whether or not the accelerating contactors open before *DB* closes because the dynamic braking armature current depends only on the braking resistance.



A-BRAKING BY NORMALLY CLOSED CONTACT ON LINE CONTACTOR



B BRAKING BY DYNAMIC BRAKING CONTACTOR



C BRAKING BY SPRING CLOSED CONTACTOR

FIG. 238. D-c dynamic braking control circuits. *M*. Line contactor. *L*. Lower contactor. *DB*. Dynamic braking contactor. *UV*. Undervoltage relay.

The coil of contactor *DB* is connected in the motor armature circuit. As soon as *M* closes, the coil of *DB* is energized. Since *DB* must not close as long as *M* is closed, it is necessary to interlock these two contactors mechanically. When *M* is dropped out, *DB* is free to close, and the counter emf of the motor keeps the contactor coil energized. During deceleration of the motor, the current through *DB* coil decreases and, as the motor approaches standstill, *DB* drops out. Connecting the *DB* contactor coil in the armature circuit has the advantage that a failure of control voltage does not prevent *DB* from closing.

Spring-closed dynamic braking contactors are used for emergency braking on hoists and the like, where the load is under the influence of gravity, and a failure of the mechanical brake may result in a run-away condition. Sketch C illustrates the basic emergency dynamic braking circuit of a master-switch-operated controller for a series motor. Dynamic braking contactor *DB* is of the spring-closed type. As long as this contactor is de-energized, a loop circuit is established connecting the armature and the series field in series with the braking resistor.

With the master switch in the off position, or in case of control power failure, *DB* drops out and establishes the dynamic braking circuit. Contactor *DB* may also be used, as shown, to obtain a shunted motor connection on the first master switch position hoisting and/or lowering, by leaving *DB* closed with all starting resistance in the motor circuit. This motor shunting obtains a reduction in light-load speeds. This feature is indicated in sketch *C*, but if it is not desired, the master switch contact controlling *DB* is arranged to close in all positions except the off position.

Plugging

Another method of bringing a motor to a stop rapidly is plugging. While the motor is running in the normal direction of rotation, the motor armature connections are reversed, and the motor develops torque in a direction opposite to the normal running torque. Instead of driving the load, the motor applies a counter torque to the load, which has the effect of retarding the load. While the motor is being plugged, the armature counter emf, instead of opposing line voltage, adds to line voltage. Nearly twice normal voltage is applied to the armature circuit at the instant the motor is plugged. To limit the armature current and torque, it is necessary to insert resistance in series with the armature during plugging. In the per unit system, the torque developed at the instant of plugging is approximately

$$T_p = \frac{2}{2R_{ia} + R_a} \qquad (68) \blacksquare$$

where T_p = initial plugging torque in per unit,
R_{ia} = internal armature resistance in per unit,
R_a = resistance in series with the armature in per unit.

In order to limit the initial plugging torque to normal torque, nearly twice normal ohms must be connected in series with the armature.

Figure 239 is the elementary diagram of a control circuit designed to obtain an automatic plug stop. Only the starting resistor is shown, and the accelerating contactors are omitted. Line contactor *M* connects the motor to the line for the normal direction of rotation. Plugging contactor *P* reverses the motor armature. As the starting resistor usually does not contain sufficient resistance to limit the plugging torque to normal, a separate plugging resistor is inserted in series with the armature during the plugging operation only.

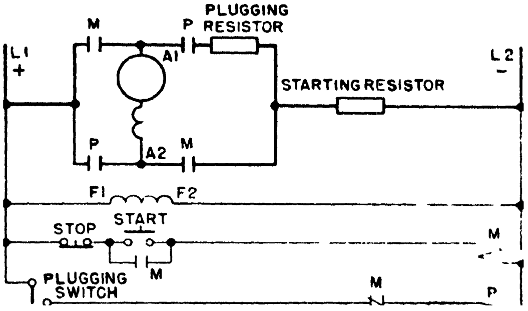


Fig. 239. Automatic plug-stop control circuits. *M*. Line contactor. *P*. Plugging contactor.

The plugging action is controlled by an automatic plugging switch, such as shown in Fig. 161. This switch is connected to the motor shaft and holds its contact closed as long as the motor rotates in the normal direction. While the motor runs with line contactor *M* closed, a normally closed interlock on *M* prevents plugging contactor *P* from closing. When the stop button is pressed, *M* and the accelerating contactors drop out. Since the plugging switch is already closed by motor rotation, contactor *P* then closes and reverses the armature connection, the plugging resistance plus the starting resistance limiting the plugging torque. The motor decelerates and as the motor reaches nearly standstill, the plugging switch opens its contact and drops out *P*, disconnecting the motor from the line. If *P* were permitted to remain closed after the motor had stopped, the motor would start in the opposite direction of rotation, load torque permitting.

Plugging is often used to obtain rapid reversing of intermittent-duty drives, such as crane travel drives, steel mill auxiliaries, and the like. Such drives are usually powered by series motors and controlled by master switches. In Fig. 240 the principal connections are shown for a reversing, plugging, five-point master-switch-operated controller for a series motor. This controller resembles an ordinary reversing controller, and the previously discussed control elements

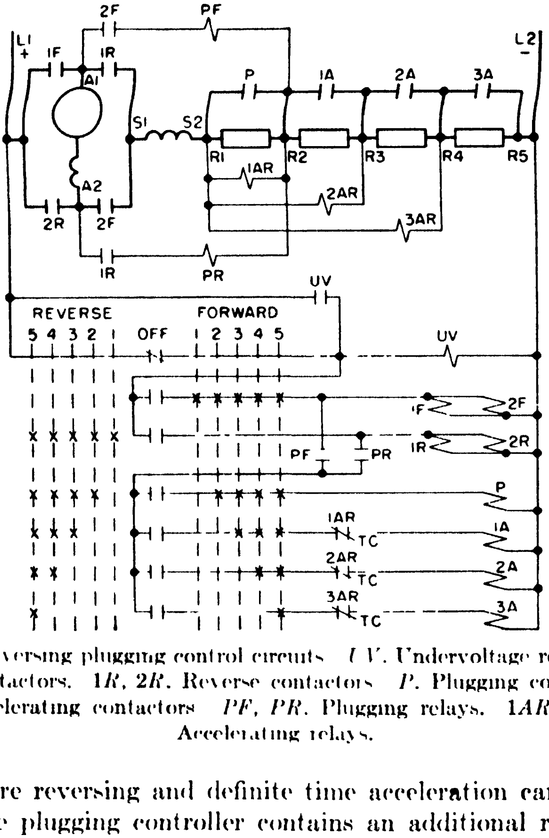


FIG. 240 Reversing plugging control circuits UV. Undervoltage relay. 1F, 2F Forward contactors. 1R, 2R. Reverse contactors P. Plugging contactor. 1A, 2A, 3A. Accelerating contactors PF, PR. Plugging relays. 1AR, 2AR, 3AR Accelerating relays.

for armature reversing and definite time acceleration can be recognized. The plugging controller contains an additional resistor section, controlled by plugging contactor *P*, which has no significance for the starting performance but has the purpose of limiting the plugging torque. Contactor *P* in turn is controlled by plugging relays *PR* and *PF*, which are voltage relays. They are interlocked with the reversing contactors so that *PF* is energized when the forward contactors are closed, and *PR* is energized when the reverse contactors are closed. Both relay coils are connected to one terminal of the resistor. In the diagram they are connected to *R*2 although, depending on the resistor lay-out, they may be connected to

*R*3. The function of these relays will be understood best by following through the sequence of operation.

Assume that the master switch is moved to the first position forward. Contactors 1*F*, 2*F* close and connect the motor to the line with terminal *A*1 positive. At the instant of starting, there is no counter emf, and full line voltage appears across the armature series resistance. Relays *PF*, 1*AR*, 2*AR*, 3*AR* pick up as there is sufficient drop across their coils to cause the relay armature to close. Moving the master switch to position two closes contactor *P* immediately. There is no time delay interposed between master switch positions one and two, as with *P* open there is only a low torque available, which may be of value to the operator to tighten up gears or the like but does not start a normal load. As the master switch is advanced to the last position forward, the accelerating contactors close with time intervals between them, as governed by the definite time-accelerating relays.

Let the master switch be turned rapidly to the fifth position in the reverse direction. The forward, plugging, and accelerating contactors drop out, and so does relay *PF*. Reverse contactors 1*R*, 2*R* close immediately and connect the motor to the line with all resistance in series with the armature. The polarity is such that motor terminal *A*2 is now connected to the positive line. Since the motor still turns in the forward direction, the counter emf adds to line voltage. The drop from *R*1 to *R*2 is approximately equal to but of opposite direction to the counter emf between *A*2 and *A*1. Thus there is practically no potential difference between *A*2 and *R*2, which means relay *PR* does not pick up and contactors *P*, 1*A*, 2*A*, 3*A* stay open. As the motor decelerates, its counter emf decreases and the potential difference between *A*2 and *R*2 increases. When the motor has decelerated to practically standstill, sufficient voltage appears across the coil of *PR* so that it closes. Contactor *P* then closes, and subsequently the accelerating contactors close in time sequence, accelerating the motor in the reverse direction.

Turning the master switch rapidly in the forward direction obtains a similar sequence, except that contactors 1*F*, 2*F* close to plug the motor. Relay *PF* functions to hold off the closing of plugging and accelerating contactors until the motor has decelerated practically to standstill.

Lay-out of Control Circuits

Although the foregoing diagrams are not complete in every detail as found on practical controllers, certain principles are involved in their lay-out which are general in nature and should be observed in the design of any controller.

1. In order to avoid sneak or back circuits, one terminal of all contactor coils should be connected solidly to one side of the line. This solid tie avoids any danger of connecting several contactor coils accidentally in series with the result that contactors may not drop out when they are supposed to drop out.
2. The foregoing leads to the requirement that all pilot device contacts and all interlocks be connected in the opposite side of the line. Thus all pilot device contacts are at the same potential, with the resultant advantage that there is no danger of breakdown of insulation between pilot device contacts.
3. On many industrial d-c power systems the negative line *L*2 is grounded. It is preferable to connect all common coil leads to line *L*2 and pilot devices in the positive side of the coils. If a ground occurs in a lead between pilot device and coil, the control line is short-circuited, but the coil is not energized. If the common coil connection were the positive side and pilot devices were in the negative coil side, a ground may cause contactors to close and start the motor inadvertently, with resultant danger to life and limb of operators.

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CHAPTER 12

BASIC ALTERNATING-CURRENT CONTROL CIRCUITS

Many of the basic control circuits for starting and accelerating a-c motors are identical with or resemble closely the corresponding d-c motor control circuits. Others are radically different because of inherent differences in motor behavior. As in the preceding chapter, commonly used basic control circuits are discussed, and the diagrams are simplified to bring out the salient features of the control function under consideration. Details not essential to the control function described are omitted, and the diagrams are not complete diagrams of actual controllers.

Control Power Sources

On controllers for low-voltage three-phase motors, the control circuits are usually connected to two primary power lines. As a matter of principle, it is immaterial which two lines are used. However, as standard controllers are designed so that they may be used for three-phase or two-phase motors, it has become accepted practice to connect the control circuits to lines *L*1 and *L*3, as control device coils are then connected across one phase of a two-phase system. On controllers for high-voltage motors, the control circuits can either be connected to the power line through a step-down control transformer or to an independent low-voltage a-c system. On either high- or low-voltage motor controllers, contactors and relays may also be used with d-c operated magnets, as discussed in Chapter 5. The control circuits are then connected to an independent d-c power source.

When a control source is used which is not connected to the power source for the motor, consideration must be given to proper undervoltage protection. Protection against failure of control voltage is based on the same principles as described for d-c controllers. Momentary contact pilot devices afford undervoltage protection inherently. Maintained-contact pilot devices provide undervoltage release, and an undervoltage relay has to be added for undervoltage protection. The motor power source, however, may fail without affecting the control source. Thus the motor may be stopped, although control connections remain established. Unless proper precautions are taken, the motor would restart automatically when motor power circuit voltage reappears. The motor power circuit should be interlocked with the control circuit so that control power is removed in case of motor power failure. It is done by connecting an undervoltage relay to the power circuit which, in case of motor power failure, interrupts the control circuit.

Starting and Jogging [1]

All a-c motors, either squirrel cage, wound rotor, or synchronous type, are started by closing the line contactor and connecting the stator to the power lines. The control circuits used for this operation are identical with the ones employed for d-c motors. The circuits given in Figs. 223, 224, and 225 for starting, jogging, and limit switch cycling can be used in a-c controllers without change.

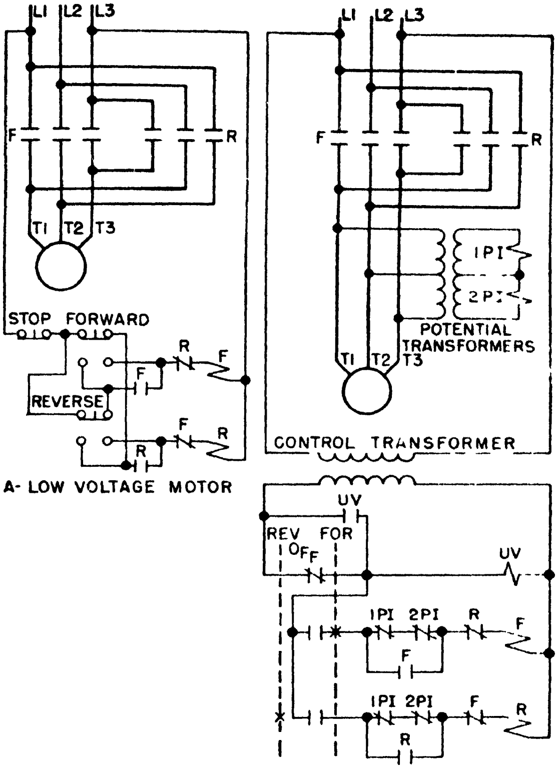
Reversing

Polyphase a-c motors are reversed by interchanging two stator leads by a pair of reversing contactors. The control circuits for low-voltage motors are similar to the reversing control circuits for d-c motors as shown in Fig. 226. Forward and reverse contactors are mechanically interlocked. It is also necessary to interlock the contactor coils electrically, as shown in Fig. 241, sketch *A*. When one of the reversing contactors is closed, the coil of the other contactor must not be energized because inrush current, if permitted to flow through the coil for an appreciable length of time, would overheat and destroy the coil.

When reversing push buttons with back contacts are used, electrical interlocking of the push buttons is often considered sufficient. When push buttons without back contacts or master switches are used, the reversing contactor coils must be interlocked by normally closed interlocks on the reversing contactors. When *F* is closed, its interlock interrupts the coil circuit of *R*. Likewise, when *R* is closed, its interlock interrupts the coil circuit of *F*. The most effective protection against short-circuiting the line and against coil burn-out is obtained if the reversing contactors are both mechanically and electrically interlocked, regardless of the type of pilot devices used.

The reversing control circuits for high-voltage motors with oil-immersed contactors are the same as for low-voltage motors, except that the contactor coil circuits are connected to the line through a control transformer or to a separate control source.

If high-voltage motors are reversed by air break contactors, electrical and mechanical interlocking is no definite insurance against possible short-circuiting of the line. On high-voltage air break contactors the arc duration is longer than on oil-immersed contactors and low-voltage contactors, and the arcs across the stationary and movable contact tips may not extinguish until after the contactors have dropped out completely. If the reverse contactor should close before the arcs on the forward contactor are extinguished, the line would be short-circuited. It can be prevented by potential interlocking, as illustrated in sketch *B*.



A- LOW VOLTAGE MOTOR

B- HIGH VOLTAGE MOTOR WITH AIR BREAK CONTACTORS

Fig. 241. A-c reversing control circuits. *UV* Undervoltage relay. *F*. Forward contactor. *R*. Reverse contactor. *1PI*, *2PI*. Potential interlocking relays.

Potential transformers are connected to the load side of the reversing contactors, and potential interlocking relays *1PI* and *2PI* are connected to the secondary side of the potential transformers. Each relay has two normally closed contacts which are connected in the coil circuits of the reversing contactors. As long as either reversing contactor is closed, or as long as any arcs exist across the contacts of either contactor, one or both potential interlocking relays are energized and their contacts are open. After one contactor has dropped out, the other contactor cannot close until after both *1PI* and *2PI* have dropped out, which means that all arcs have been extinguished. The contactors seal themselves in through normally open interlocks which bypass the potential interlocking relay contacts.

Reduced Voltage Starting

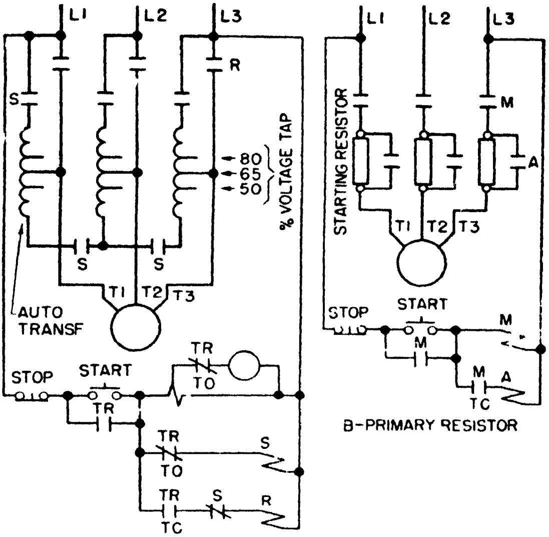
In Chapter 3 it is explained how the starting current of squirrel cage motors can be reduced by applying reduced voltage to the motor stator. The methods used to obtain reduced voltage are:

1. Auto-transformer.
2. Primary resistor.
3. Primary reactor.

Basic control connections for reduced voltage starting are illustrated in Fig. 242.

Auto-transformer starters, also called starting compensators, require two contactors. See sketch *A*. Start contactor *S* has five poles. It connects the transformer to the line and closes its wye point. The motor is connected to taps on each leg of the transformer, so that the motor terminal voltage is reduced below line voltage. Standard auto-transformers are equipped with either two taps for 65 per cent and 80 per cent of line voltage, or with three taps for 50 per cent, 65 per cent, and 80 per cent of line voltage. Run contactor *R* connects the motor stator to full-line voltage. Since the connection between the motor stator and the auto-transformer taps is not broken while the motor is running on full voltage, it is necessary to break the wye point of the transformer to prevent high current from circulating through part of the transformer winding.

The control sequence is as follows: First, the start contactor closes. After a time delay, sufficient to permit acceleration of the motor, the start contactor drops out and the run contactor closes. Various arrangements of control circuits are possible, depending on the method chosen for obtaining the time delay at which the transition from the start to the run connection occurs. The control circuit shown in sketch *A* makes use of a motor-driven timing relay, of a type illustrated in Fig. 127, which is suitable for long time delays required for starting high-inertia loads. Pressing the start push button energizes timing relay *TR*. An interlock, which closes instantaneously, seals in the relay. Start contactor *S* closes, its coil being energized through normally closed contact of *TR*. The relay then starts timing. After a time interval, for which the relay is set, the normally closed contact opens and drops out contactor *S*. At the same time the normally open time delay contact of *TR* closes and energizes contactor *R* through a normally closed interlock on *S*. Thus *R* closes immediately after *S* opens, and the two contactors do not overlap. This is important, as an overlapping of *R* and *S* would cause high current to flow in the transformer windings, resulting in high mechanical stresses.



B–PRIMARY RESISTOR

A–AUTO TRANSFORMER

FIG. 242. A-c reduced voltage starting control circuits. *S*. Start contactor. *R*. Run contactor. *M*. Line contactor. *A*. Accelerating contactor. *TR*. Definite time relay

In a primary resistor starter, the drop due to the inrush current in a resistor in series with the motor stator winding obtains reduced starting voltage at the stator terminals. See sketch *B*. The motor is first connected to the line through line contactor *M*, with the resistor in series. After a time delay, accelerating contactor *A* closes and short-circuits the starting resistor. As primary resistor starters are generally used for small and medium-size motors, a short time delay is sufficient. The control circuit of sketch *B* realizes the following starting sequence. When the start button is pressed, contactor *M* closes and seals itself in. Mechanically coupled to the contactor shaft is an interlock which, through an escapement gear, closes a definite time after the main contacts have closed. Contactor *A* is energized through this time-closing interlock.

Primary reactor starters are similar to primary resistor starters, except that a reactor takes the place of the resistor. As reactor starters are being used more and more for large motors, long-time delay relays are required to control the closing of the accelerating contactor short-circuiting the reactor.

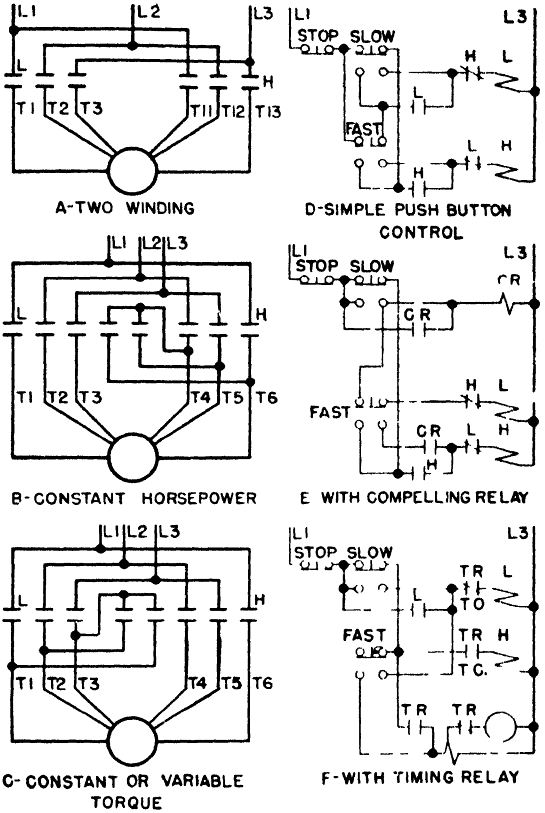
Pole Changing

Control of multi-speed squirrel cage motors comprises a considerable number of variants, depending on the design characteristics of the motors. Consider first the power connections of the stator and refer to Fig. 66 for types of motor windings. Some of the most commonly used power circuits for two-speed motors are indicated in Fig. 243. Connections are very simple when the stator winding consists of two superimposed circuits, shown in sketch *A*. A pair of triple-pole contactors, *L* for low speed and *H* for high speed, connect either stator winding to the line. For motors with consequent pole stator windings, one three-pole and one five-pole contactor must be used. With constant horsepower motors the low-speed contactor has five poles and the high-speed contactor has three poles as is indicated in sketch *B*. With constant or variable torque motors, the low-speed contactor has three poles and the high-speed contactor has five poles, as shown in sketch *C*. Stator connections for motors with more than two speeds are combinations of those shown in the diagrams of Fig. 66.

As far as control connections are concerned, several basic circuits exist, their application depending on starting torque and current of the motor under consideration and the requirements of the drive. Several control circuits are given in Fig. 243, and any of the control circuits may be used in connection with any of the stator power circuits.

When starting currents of both stator windings are moderate and the drive may be started on either high speed or low speed, the simple push button circuit of sketch *D* can be used. Pressing the slow or fast push button energizes contactors *L* or *H*, respectively. When the motor runs at low speed and the fast push button is pressed, contactor *L* drops out and contactor *H* closes, and the motor accelerates to high speed. Conversely, if the motor runs at high speed and the slow push button is pressed, contactor *H* drops out and contactor *L* closes, and the motor decelerates to its slow speed.

For some drives the starting torque of the high-speed winding is too low and the motor must be started on the slow-speed winding


A-TWO WINDING

B-CONSTANT HORSEPOWER

C-CONSTANT OR VARIABLE TORQUE

D-SIMPLE PUSH BUTTON CONTROL

E WITH COMPELLING RELAY

F-WITH TIMING RELAY

FIG. 243. Pole changing control circuits *L*. Low-speed contactor *H* High-speed contactor. *CR*. Compelling relay. *TR*. Definite time relay

before the high-speed winding can be energized. It can be accomplished by the use of a compelling relay as shown in sketch *E*. Pressing the slow button closes compelling relay *CR*, which seals itself in and energizes contactor *L*. When the fast button is pressed, contactor *L* is dropped out, but relay *CR* stays closed. Contactor *H* is energized through an interlock on *CR*. When the slow push button is then pressed, *H* is de-energized and *L* closes again. If, however, the fast push button is pressed, without the slow button having been pressed first, nothing happens, as *H* cannot close unless *CR* has been closed first.

The control circuit just described requires the pressing of two push buttons in proper sequence to accelerate the motor to its maximum speed. This inconvenience is avoided by the use of a timing relay as illustrated by sketch *F*. When the slow push button is pressed, contactor *L* closes and the motor starts on the slow-speed winding. If the fast push button is pressed, a motor-driven timing relay *TR* is energized, which seals itself in through an instantaneous interlock. Contactor *L* is energized simultaneously through the normally closed contact of *TR*. After relay *TR* has timed out, its normally closed contact opens, dropping out *L*. The normally open contact of *TR* closes, causing *H* to close. The motor is thus accelerated in time-controlled sequence to its high speed by pressing one push button only.

Multi-speed motors are reversed by a pair of reversing contactors, the power contacts of which are connected in series with the pole-changing contactors. Motors may run in either direction at either speed. If the starting current on either or both the high- and low-speed windings is too high, primary resistance and accelerating contactors are added to either or both stator circuits. The additional control circuits are the same as described for primary resistance starting.

It should be remembered that, when connections are changed from the high-speed to the low-speed winding, the motor operates at a multiple of the synchronous speed of the low-speed winding. A high retarding torque, accompanied by a high current peak, is developed by the motor as it slows down; such torque and current peaks may be excessively high for the drive. A primary buffer resistor can be inserted in the low-speed winding, which is short-circuited by a contactor in time sequence to reduce the retarding current and torque peaks and make deceleration smoother.

Acceleration[1]

Squirrel cage motors, once they are connected to the line, accelerate according to their inherent speed-torque characteristics, which cannot be controlled by extraneous means. Acceleration of wound rotor motors, which are started with external resistance in the rotor circuit, can be controlled by the manner in which the secondary resistance is short-circuited.

Speed-torque characteristics of wound rotor motors are very similar to those of shunt-wound d-c motors as has been explained in

Chapter 3. The speed-torque curves can be considered as straight lines, at least within the torque range commonly used for acceleration, which is up to twice normal. The slip or drop in speed below synchronous at full-load torque, expressed in per unit, is equal to the total resistance per leg in the rotor circuit, also expressed in per unit. See Fig. 78 for speed-torque curves with various amounts of secondary resistance. Performance of a wound rotor motor during acceleration is also represented by Fig. 229. In sketch B, YA equals the per unit internal rotor resistance per phase, and AC, CE, and EG are the per unit resistance per phase of various steps of the starting resistor. The general theory of acceleration given in Chapter 11 applies also to wound rotor motors.

Depending on the criterion used for controlling the closing of the secondary accelerating contactors, the following methods of accelerating control are available:

1. *Current limit control.* Contactor closing is governed by current limit relays which permit the accelerating contactor of each step to close when the motor current has dropped from a peak value to a preset lower value.

2. *Secondary frequency control.* As the motor accelerates from standstill to full speed, the frequency of the rotor circuit drops from line frequency to a few cycles. Frequency responsive relays permit accelerating contactors to close as the motor reaches predetermined speeds.

3. *Definite time control.* Closing of accelerating contactors occurs in sequence with definite time intervals between them, the timing being adjusted so as to obtain uniform accelerating current peaks.

In the following paragraphs the basic connections of starters using the above accelerating control methods are described. The elementary diagrams show only such circuit details as are necessary to illustrate the basic control systems. Actual starters include additional elements, especially protective devices, which are omitted for the sake of simplicity.

Current limit acceleration uses relays measuring the stator or rotor current to control the closing of the accelerating contactors. The differences between d-c and a-c current limit starters are due to the design of the current limit relays. One form of current limit acceleration controller is shown in Fig. 244. Accelerating relays 1*AR* and 2*AR*, which are illustrated in Fig. 128 and whose functions are described on page 190, determine the details of the control circuits. Each relay has a current coil which is connected to one motor stator phase, either directly or through a current transformer. The current coil is calibrated so that its plunger drops out and permits closing of the relay contact when the motor current has dropped to a predetermined value, usually between 100 per cent and 125 per cent of full-load current. The plunger of the potential coil, when dropped out, prevents the relay from closing, regardless of the condition of the current coil. When the potential coil is energized and its plunger is picked up, the relay contact is solely under the control of the current coil plunger.

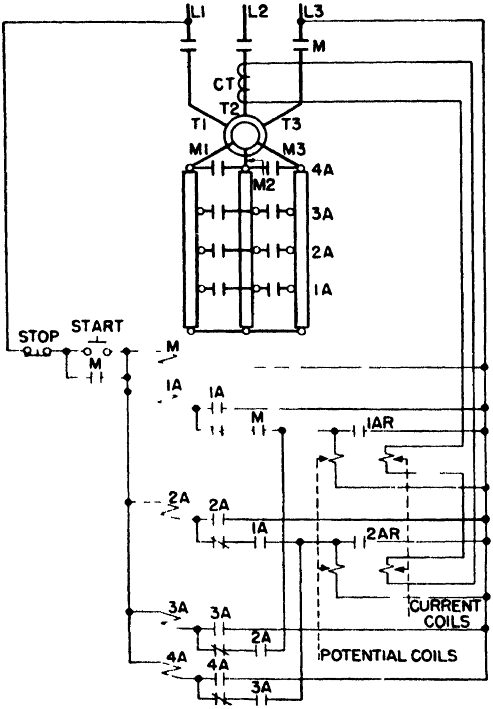


FIG. 244. Starting control circuits with current limit acceleration. *M*. Line contactor. 1*A*, 2*A*, 3*A*, 4*A*. Accelerating contactors. 1*AR*, 2*AR*. Accelerating relays. *CT*. Current transformer.

With the motor de-energized, potential and current coils of relays 1*AR* and 2*AR* are de-energized, and the contacts of both relays are open. Pressing the start button causes contactor *M* to close. The inrush current of the motor picks up the current coil plunger of both relays 1*AR* and 2*AR*. Through an interlock on *M* the potential coil of relay 1*AR* is connected in series with the coil of contactor 1*A*. Since the impedance of 1*A* coil is low and the impedance of 1*AR* potential coil is high, the resultant current is insufficient to close 1*A* but sufficient to pick up the potential coil plunger of 1*AR*. When the motor current drops to the preset value, the current coil plunger drops out, relay 1*AR* closes its contact and connects 1*A* coil directly across the control source so that 1*A* closes. 1*A* seals itself in, and a normally closed interlock breaks the connection between 1*A* coil and 1*AR* potential coil so that the potential coil plunger of 1*AR* drops out and the relay contact opens.

When 1*A* closes, an interlock connects the coil of contactor 2*A* in series with the potential coil of relay 2*AR*. The closing of 1*A*, however, has caused an increase in motor current so that the current coil of 2*AR* takes control and keeps 2*AR* contact open. When the current drops again to the preset value, 2*AR* closes its contact. 2*A* closes, sealing itself in and breaking the connection between 2*A* coil and 2*AR* potential coil. At the same time the coil of contactor 3*A* is connected in series with potential coil of relay 1*AR*, but the contact of that relay stays open because of the current peak due to 2*A* closing As the current drops, 1*AR* permits 3*A* to close. Contactor 4*A* is then connected to relay 2*AR*, and that relay governs the closing of 4*A*.

Two accelerating relays suffice to control any number of accelerating contactors. They function alternately, and odd-numbered contactors are controlled by relay 1*AR*, whereas even-numbered contactors are controlled by relay 2*AR*. One precaution must be observed. It is very essential that the electrical interlocks of the accelerating contactors are adjusted so that the normally open contacts close slightly before the normally closed contacts open, and this adjustment must be maintained. A refinement, which is not indicated in Fig. 244 but is found on practical controllers, is the addition of a small holding coil in series with the accelerating relay contacts which insures good contact pressure and safeguards against possible chattering of the relay contacts.

While a wound rotor motor accelerates to full speed, its secondary voltage drops from standstill voltage to nearly zero, and its secondary frequency drops from line frequency to nearly zero, both voltage and frequency being proportional to the slip. Thus, by devising relays which respond to the rotor voltage and frequency condition, the closing of accelerating contactors can be made a function of motor speed, similar to the counter emf method of acceleration used on d-c controllers.[2]

In Fig. 245 accelerating relays 1*AR*, 2*AR*, 3*AR*, 4*AR* are connected in the secondary circuit. Each relay coil is connected through a capacitor to a potentiometer resistor, which in turn is connected across one leg of the starting resistor. The inductance of each relay coil, in combination with the capacitor, forms a resonant circuit so that a high current flows within a certain frequency range, the band width of the frequency range being determined by the adjustment of the resistor. When the frequency drops below the resonant frequency range, the relay coil current drops as a function of frequency, the actual current being adjustable by shifting the potentiometer resistor tap.

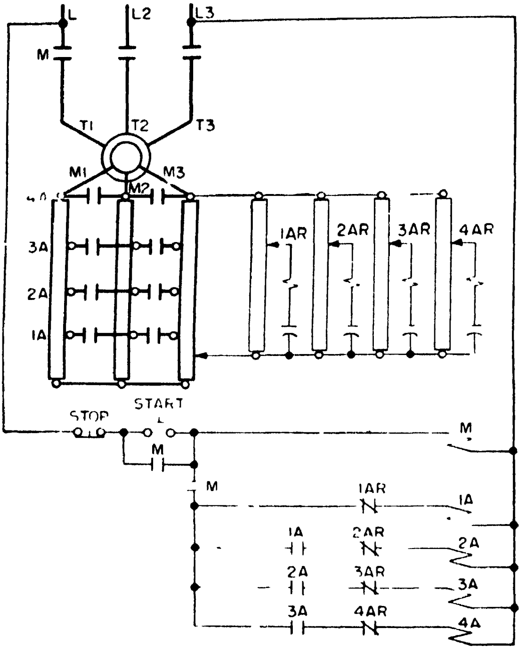


FIG. 245 Starting control circuits with acceleration by frequency responsive relays. *M*. Line contactor. 1*A*, 2*A*, 3*A*, 4*A*. Accelerating contactors. 1*AR*, 2*AR*, 3*AR*, 4*AR*. Accelerating relays.

With the motor de-energized, the accelerating relays are dropped out. When the start button is pressed and line contactor *M* closes, line frequency is applied to the accelerating-relay coils, a high current flows in the relay coils, and all relays open their contacts immediately. As the motor accelerates the relay coil currents drop, and, by proper adjustment, relays 1*AR*, 2*AR*, 3*AR*, 4*AR* drop out at predetermined secondary frequencies, that is, at predetermined motor speeds, causing the accelerating contactors to close in sequence.

The objections raised in Chapter 11 against current limit and counter emf acceleration control apply to a-c starters also. Both current limit and frequency relays depend for their proper performance on the condition that the motor must start on the first controller step. Otherwise the accelerating contactors are prevented from closing. Definite time control of acceleration overcomes this disadvantage, as accelerating contactors will close in sequence until maximum torque is reached, forcing the motor to start on subsequent controller steps.

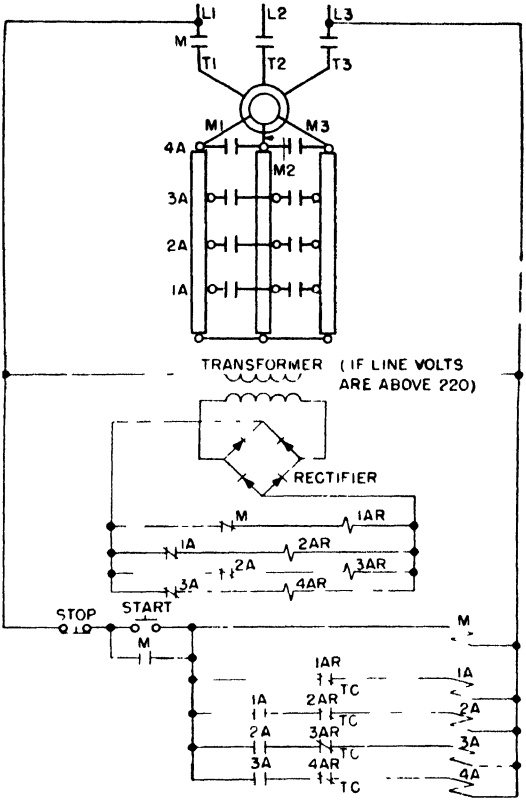


FIG. 246. Starting control circuits with acceleration by definite time relays. *M*. Line contactor. 1*A*, 2*A*, 3*A*, 4*A*. Accelerating contactors. 1*AR*, 2*AR*, 3*AR*, 4*AR* Accelerating relays.

Mechanical timers are used widely on controllers designed for infrequent starting. A multiple contact relay, closing its contacts in definite time sequence, may be used to close accelerating contactors in sequence. As an alternative, each contactor, that is, line contactor and accelerating contactors, may be equipped with mechanically operated interlocks, which close their contact a definite time after the contactor closes. Thus, each contactor will sequence-in the subsequent contactor, with definite time intervals between contactors.

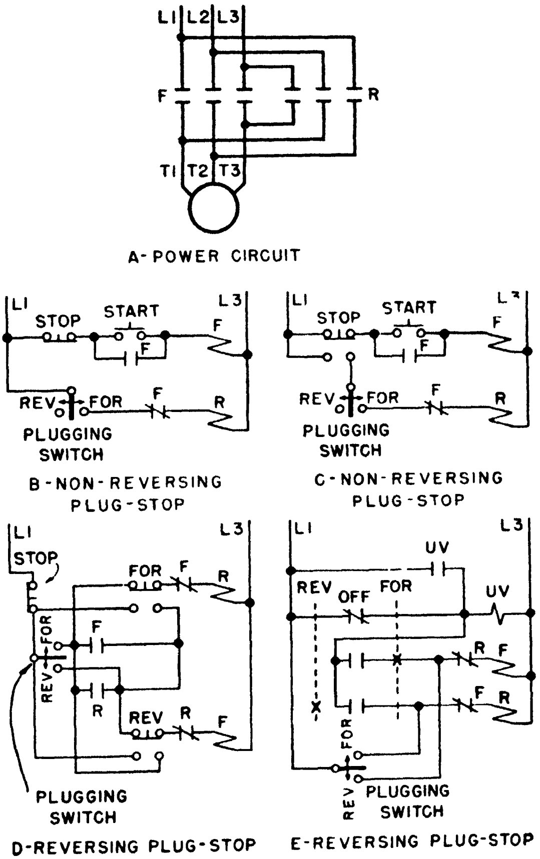
An inherent disadvantage of mechanical timers is their comparatively short life, which is only a fraction of the life which can be expected of the contactors. It makes mechanical timers and time delay interlocks undesirable for controllers designed to start a motor frequently. Magnetic time delay drop-out d-c relays, as shown in Fig. 108, have found considerable application on a-c controllers, especially for intermittent drives, such as cranes, mine hoists, car dumpers, steel mill auxiliaries, and the like. A supply of direct current must be provided for the relay coils. In Fig. 246 the accelerating relay coils are connected to a metallic rectifier, which is connected directly to the control lines, or through a transformer, if the control voltage is higher than 220 volts. The rectifier can be omitted if a separate d-c control supply is available for operating the contactors.

With the motor at standstill, all accelerating relays are energized, and their contacts are open. When *M* closes upon pressing the start push button, coil 1*AR* is de-energized through a normally closed interlock on *M*. Relay 1*AR* drops out and closes its contact with a time delay, causing contactor 1*A* to close. Coil 2*AR* is then de-energized, relay 2*AR* drops out with a time delay, and causes contactor 2*A* to close. In a similar manner, contactors 3*A* and 4*A* close with time intervals between them, as governed by relays 3*AR* and 4*AR*.

Plugging[5]

Many a-c motor controllers include provision for plugging both for quick stopping and for rapid reversing. Plugging control of squirrel cage motors is very simple. It is necessary only to reverse the stator connections, and no further power switching is required. See Fig. 71 for typical plugging curves of squirrel cage motors. Whether or not a given squirrel cage motor is suitable for plugging service depends on the load, especially its inertia, and the thermal capacity of the motor rotor. The handbooks of motor manufacturers include data for selecting motors for plugging service. To plug a motor, a pair of reversing contactors is provided to reverse the stator connections, as shown in sketch *A* of Fig. 247. Any reversing controller can be used for plugging the motor manually. See Fig. 241.

Suppose the motor runs in the forward direction. Pressing the reverse button drops out the forward contactor and closes the reverse contactor. The motor is then plugged. When the motor has come to a standstill, the stop button may be pressed, bringing the motor



A-POWER CIRCUIT

B-NON-REVERSING PLUG-STOP

C-NON-REVERSING PLUG-STOP

D-REVERSING PLUG-STOP

E-REVERSING PLUG-STOP

FIG. 247. Plug-stop control circuits for squirrel cage induction motor. *UV*. Undervoltage relay. *F*. Forward contactor. *R*. Reverse contactor.

to a plug-stop; or the motor may be permitted to accelerate in the reverse direction, and plugging is then used for rapid reversal.

Automatic plugging to a stop is accomplished by the use of a plugging switch such as is illustrated in Fig. 161, which is coupled to the motor shaft. Several automatic plugging control circuits are indicated in Fig. 247. See sketch *B*, which applies to an automatic plug-stop control for a non-reversing drive. When the start button is pressed, contactor *F* closes, which connects the motor to the line in the forward direction and interrupts the coil circuit of contactor *R* through a normally closed interlock. As the motor starts rotating, the plugging switch closes its forward contact. When the stop button is pressed, contactor *F* is dropped out, and contactor *R* closes, since its coil is energized through the plugging switch. The motor stator connections are reversed, and the motor develops a counter torque, opposed to the load torque, which results in rapid retardation. When the motor speed has dropped to nearly zero, the plugging switch opens and contactor *R* is dropped out.

Sketch *C* shows a modified circuit, which permits the motor either to coast to a stop or to be plugged to a stop. If the stop button is pressed and then released again, contactor *F* drops out and contactor *R* does not close. The motor simply coasts until it is stopped by friction. If the stop button is pressed and held depressed, so that its normally open contact is closed, contactor *F* drops out, but contactor *R* is closed through the plugging switch and the motor develops counter torque until it is disconnected from the line when the plugging switch opens.

In sketch *D* connections are shown for obtaining automatic plug-stop on a push-button-operated reversing controller. Pressing the forward button energizes contactor *F*. The button must be kept depressed until the motor has started, as the holding circuit is closed through the forward contact of the plugging switch. Pressing the stop button causes contactor *F* to drop out, and contactor *R* is energized through the plugging switch. Conversely, if the motor had been started in the reverse direction, contactor *R* is sealed in through the reverse contact of the plugging switch. When the stop button is pressed, contactor *R* drops out and contactor *F* is energized through the plugging switch. Automatic plug-stop is obtained in both directions of rotation.

A similar arrangement is indicated in sketch *E* for a master-switch-operated reversing controller. Centering the master switch from either direction of rotation causes the contactor for opposite rotation to be energized through the plugging switch.

When wound rotor motors are plugged, it is necessary to insert sufficient resistance in the secondary circuit to limit both the motor current and torque to a safe value. Figure 78 shows that enough resistance must be provided so that the motor torque and the motor current at normal speed in the negative direction are not higher than the torque at standstill; otherwise the motor current would be excessive. If it is assumed that sufficient resistance is provided so that the motor speed-torque curve is a straight line between standstill and unity negative speed, the torque developed at the instant of plugging in per unit is approximately

$$T_p = \frac{2}{2R_i + R_s} \qquad (69)$$

where T_p = per unit motor torque,
R_i = per unit internal rotor resistance per leg,
R_s = per unit resistance per leg in series with rotor.

Formula 69 is identical with formula 68, indicating the close resemblance in plugging performance between d-c shunt motors and a-c wound rotor motors.

On most applications it is desirable to limit the initial plugging torque to normal torque. The external secondary resistor should then include a total resistance of approximately two per unit ohms.

The plug-stop connections of Fig. 247 can be used also for wound rotor motors, as far as the control of the stator connections is concerned. The control circuits for the secondary contactors must be arranged so that the secondary contactors cannot close while the motor is plugged to a stop.

On intermittent reversing drives, for instance bridge and trolley drives of cranes, the operator is given the choice of coasting, or plugging to a quick stop, or reversing rapidly by plugging. A plugging switch cannot be used, as it would prevent the desired flexibility, and some other relay must be used to control the secondary contactors during the plugging operation. A control circuit, suitable for reversing plugging, is shown in Fig. 248. A five-point master switch serves as a pilot device, and the control circuits include the previously discussed elements for reversing and definite time acceleration by means of magnetic time delay drop-out d-c relays. There is one additional secondary resistor section which is short-circuited by plugging contactor *P*. The total resistance of the secondary resistor is approximately twice base resistance, so that the starting current with all resistance in the rotor circuit is approximately one half normal. Contactor *P* is under the control of plugging relay *PR*, which is a current limit type of relay, the same as used for current limit acceleration (see Fig. 244).

Operation of the control system is as follows: Turning the master switch in the forward direction to the first position closes contactor *F*, the motor draws approximately one half full-load current, and the current coil plunger of relay *PR* is not picked up. Advancing the master switch to the second position energizes the potential coil of relay *PR*, which closes its contact. Contactor *P* then closes and seals itself in. Turning the master switch to the fifth position closes

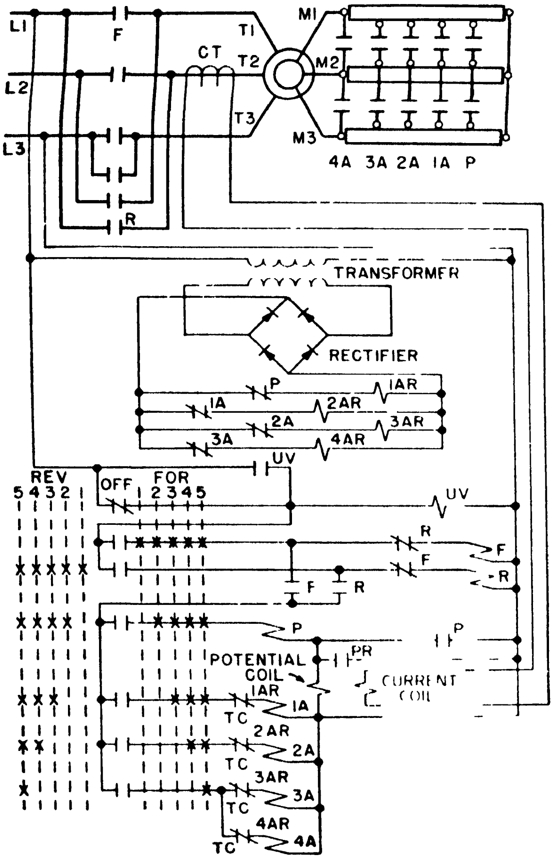


FIG. 248. Reversing plugging control circuit for wound rotor induction motor. *F*. Forward contactor. *R* Reverse contactor. *P*. Plugging contactor. 1*A*, 2*A*, 3*A*, 4*A*. Accelerating contactors. *UV*. Undervoltage relay. *PR*. Plugging relay. 1*AR*, 2*AR*, 3*AR*, 4*AR*. Accelerating relays.

the accelerating contactors in definite time sequence, as governed by the accelerating relays. When the master switch is now turned rapidly to the last position reverse, all contactors drop out and contactor *R* closes. At the instant of plugging, the motor current is equal to approximately full-load current. Relay *PR* is adjusted so that the current coil plunger stays up and neither contactor *P* nor the accelerating contactors can close, and the total secondary resistance remains inserted in the rotor circuit. As the motor decelerates, its torque and current gradually decrease until one half normal is reached at standstill. Relay *PR* is adjusted to close at approximately 0.65 of normal current. Thus contactor *P* is permitted to close when the motor has been retarded to a slow speed. The accelerating contactors then close in definite time sequence, and the motor accelerates in the reverse direction. Corresponding performance is obtained when the master switch is moved from any position reverse to any position forward.

Dynamic Braking[6, 7]

A-c motors can be retarded by disconnecting the stator from the line and exciting the stator winding from a suitable source of direct current. A simple control circuit for dynamic braking of squirrel cage motors to a stop is given in Fig. 249. For normal running, contactor *M* is closed and *DB* is open. When the stop button is pressed, contactor *M* is dropped out. If the button is only lightly pressed, the motor coasts to a stop. If, however, the button is pressed

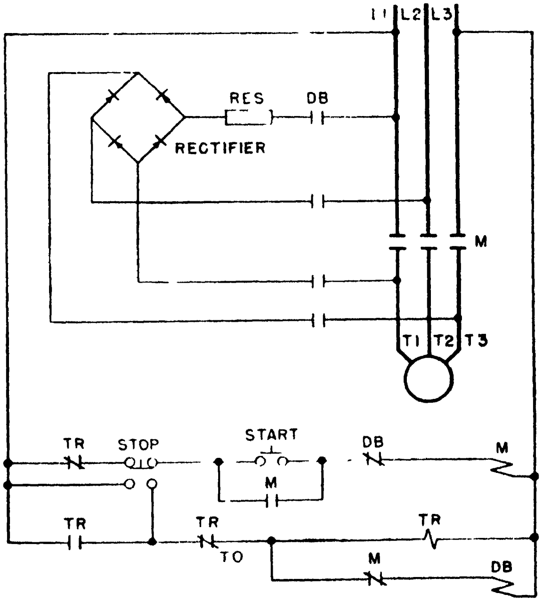


FIG. 249. D-c dynamic braking control circuits for squirrel cage induction motor. *M*. Line contactor. *DB*. Dynamic braking contactor. *TR*. Definite time relay.

all the way down so that its normally open contact closes, a mechanical timing relay *TR* and dynamic braking contactor *DB* close. *DB* connects a metallic rectifier to the line, and two lines of the motor stator are connected to the d-c side of the rectifier.

Relay *TR* has a normally closed interlock, which opens instantaneously and makes the start button ineffective so that the line contactor cannot be energized while *TR* is timing. An instantaneously closing, normally open contact on *TR* seals in the timing relay so that the stop button may be released. After a definite time delay, which permits the motor to come to rest, *TR* opens its time-opening contact. This drops out relay *TR* and contactor *DB*. D-c excitation is removed, and the motor is ready for a new start.

Contactors *M* and *DB* must never be closed at the same time. Thus *M* and *DB* are electrically and mechanically interlocked against each other.

When d-c dynamic braking is applied to a wound rotor motor, the speed and torque can be varied by changing the amount of secondary resistance or, in other words, by opening and closing accelerating contactors. This makes d-c dynamic braking suitable for hoists on which the load, when lowered, overhauls the motor. Exciting the motor stator from a constant potential d-c source and varying the secondary resistance permit controlling the lowering speed. For typical speed-torque curves which can be obtained with this type of control, see Fig. 81.

The principal control circuits for dynamic braking of a wound rotor motor driving a hoist are indicated in Fig. 250. A master switch is used so that the operator has manual control of the motor speed. To obtain high lowering speeds, a considerably larger amount of secondary resistance is required than would be used to obtain a starting torque desirable for hoisting. Thus five accelerating contactors are provided, whereas only four would be required to start the motor hoisting. A source of direct current must be available for the stator excitation. Either a rectifier or a small motor generator set could be used, the choice being governed primarily by economic considerations. As the proper functioning of the control depends upon direct current being available, a d-c undervoltage relay *DCUV* is connected to the d-c source, and its contact is connected in series with the regular undervoltage relay *UV* coil, so that the control is inoperative unless the d-c source is alive.

Turning the master switch in the hoisting direction obtains conventional acceleration performance. Contactor *H* connects the motor stator to the line. Contactor 1*A* closes immediately on the first master switch position, in order to short-circuit a block of resistance which is not required for hoisting. The other accelerating contactors close on subsequent master switch positions, and definite time-accelerating relays provide time intervals between contactors. The coils of the accelerating relays are connected to the d-c source.

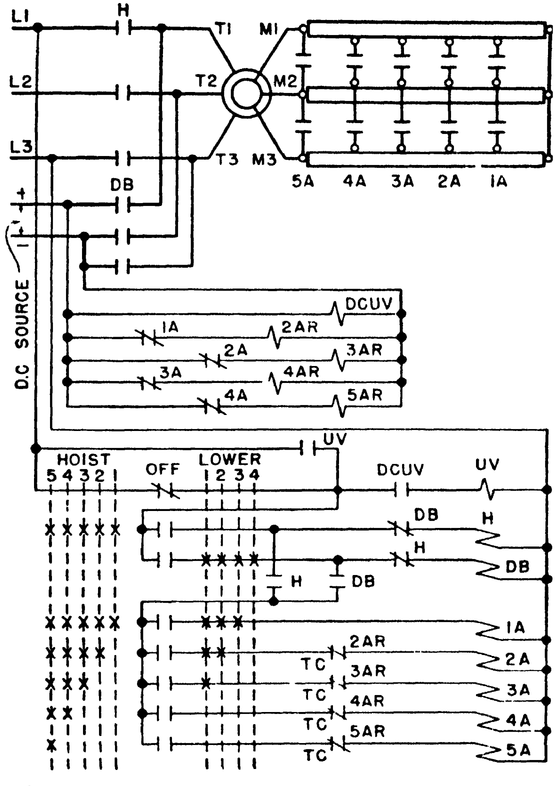


FIG. 250. D-c dynamic braking control circuits for wound rotor induction motor. *H*. Hoist contactor. *DB*. Dynamic braking contactor. *1A*, *2A*, *3A*, *4A*, *5A*. Accelerating contactors. *2AR*, *3AR*, *4AR*, *5AR*. Accelerating relays. *UV*. Undervoltage relay. *DCUV*. D-c undervoltage relay.

In the lowering direction, contactor *DB* closes and connects the motor stator to the d-c supply. On the first master switch position, contactors *1A*, *2A*, *3A* close, and the motor accelerates to the lowest speed in the lowering direction. The number of accelerating contactors closed on this point depends on the desired lowering speed, which determines how much resistance should be left in the circuit. Advancing the master switch causes *3A*, *2A*, *1A* to drop out in sequence, and the motor speed increases. Turning the master switch back toward the off position causes contactors 1*A*, 2*A*, 3*A* to close again, and the accelerating relays govern the time sequence and thus the rate of deceleration. This delay in contactor sequencing is important, as too rapid closing of the accelerating contactors would cause the motor to "go over the hump" of the speed-torque curves, which might result in a run-away condition.

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CHAPTER 13

AMPLIDYNE CONTROL CIRCUITS

The fundamentals of amplidyne performance are explained in Chapter 2. Because of their high amplification factor and speedy response, amplidynes can be used advantageously as regulators in closed cycle control systems. The power required for the excitation of amplidyne fields is so small that impulses of such low energy can be used in the control circuits that the drain on the system to be regulated is negligible. Regulating circuits can be devised which not only obtain a desired operating quantity at a certain load condition but which also maintain such quantity over a wide load range. This requires circuits quite different from the control circuits heretofore described.

In a closed cycle control system a standard is established which determines the operating quantity to be maintained, for instance, voltage of a generator or speed of a motor. Against this standard is balanced a signal which measures the actual operating quantity such as generator voltage or motor speed. A deviation of the actual operating quantity from the standard initiates a corrective action designed to minimize the deviation from the standard. A deviation must exist to obtain regulating action, or, in other words, deviation from the standard can be minimized but not entirely prevented.

Most amplidynes in industrial applications are used to excite generators of adjustable-voltage systems for the purpose of obtaining a certain desired motor performance. Most commonly, the purpose is to maintain speed independent of load or to vary speed as a function of some other operating quantity.

The error of a regulating system is defined as the maximum deviation of the actual performance quantity from the standard, which will not initiate regulating action. The smaller the error, the smaller is this deviation. In industrial control systems, errors between plus or minus 1 per cent and plus or minus 2 per cent are commonly obtained with straight amplidyne circuits, responding to correction signals of a few watts. Higher accuracies can be realized by using a second amplidyne as an amplifier or by introducing an electronic amplifier ahead of the amplidyne. Such systems are able to respond to correction signals as low as plus or minus 0.5 per cent of the quantity to be regulated.

Speed of response is the time required to reach a final correction. It depends on the time constant of the regulating circuit and the combined time constants of the system. For instance, in an adjustable-voltage control system the generator field has a time constant which determines the rate of change of its flux, and consequently of generator voltage, after voltage impressed on the generator field excitation has been changed. Likewise, the mechanical time constant of the motor and its connected inertia load determine the rate of change in speed consequent to a change in motor voltage. Thus the speed of response of a system is not determined by the speed of response of the regulating circuit alone, but the combined electrical and mechanical time constants of the various components of the system must be considered. The speed of response of the amplidyne regulating circuit itself depends on the rate of amplification used in the system and the circuit design. Generally speaking, the speed of response of conventional amplidyne regulating circuits is of the order of 0.20 to 0.30 second. Increasing the amplification increases the time of response. The addition of vacuum tube amplifiers or amplidyne amplifiers increases the delay in the regulating circuit very little.

To illustrate the practical significance of error and speed of response, consider a flying shear in a steel mill. Error of control of the shear motor speed determines the uniformity in length of the cut bars. Speed of response governs the recovery of motor speed, which drops under the impact of the load at each cut of the shear.

"Forcing" or initial overexciting of the amplidyne is provided as an inherent feature of a good regulating system in order to obtain fast response at the instant of starting or when major changes in speed are required. It is of importance on intermittent drives. At the instant of starting, maximum deviation exists between the operating quantity (that is, speed zero) and the standard. The excitation applied to the controlled field is a multiple of the excitation required to sustain that field, and a fast build-up is obtained. Most applications use forcing of three to four times normal field current, although, on regulating systems designed for low error, forcing as high as twenty times has been used.

Stabilizing

Regulating systems are likely to "hunt." When the correction signal is received, the system tries to reach the standard as fast as it can, and it may overshoot. Then the regulator tries to correct for the overshoot, and as a result it undershoots. As a consequence, the regulator may set up around the standard an oscillation of alternate overshooting and undershooting. The feed-back signal from the system, which is required to minimize the deviation from the standard, then supplies the necessary energy to sustain the oscillations, which are system wide; the frequency of these oscillations is determined by the constants of the system. Such a regulator is unstable. On the other hand, the regulator may overshoot and undershoot a few times, with decreasing amplitude of oscillation, until a steady state value is reached. Such a regulator is damped. Or the regulator may approach the steady state value without any oscillation, in which case the regulator is critically damped. A regulator which is damped and does not sustain oscillations is called a stable regulator.

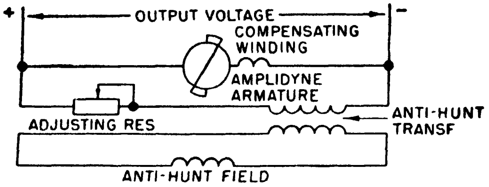
Whether or not a regulator hunts depends not only on the regulator itself but also on the electrical and mechanical constants of the whole system that is regulated. Inductance, capacitance, and resistance as well as inertia and friction have an effect. Analytical methods have been proposed to determine whether a given system will hunt. Such calculations are quite complicated and cumbersome. Often it is impossible to determine accurately the system constants entering into the calculations. For practical purposes, it is rather difficult, if not impossible, to calculate rigorously by pure analysis whether or not a given system will hunt.

In designing a regulating circuit, past experience and calculations based on data gathered by tests on installations largely govern the engineer's judgment as to whether hunting is to be expected. The best method to safeguard against hunting is to provide certain features in the control system which make it possible, by proper adjustment, to "anti-hunt" or stabilize the system, should hunting occur after the equipment has been placed in service.

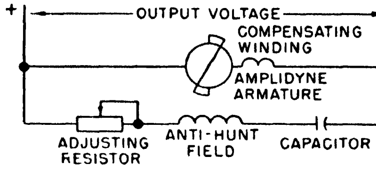
Generally speaking, the higher the accuracy of the regulator, and the faster its speed of response, the greater is the probability that the system will hunt. Any regulator can be stabilized by *desensitizing* it, that is, by impairing its error and speed of response. Desensitizing should be avoided if at all possible, as it reduces the quality of the regulator.

Most anti-hunting or stabilizing systems make use of a feed-back signal, the magnitude of which is proportional to the rate of change of the regulator output, introduced into the regulator circuit in such a sense as to oppose the change in output. Anti-hunting slows down the change in output of the regulator and minimizes the tendency to overshoot without affecting the ultimate output quantity, and with only a slight decrease in the speed with which the steady state ouput is reached.

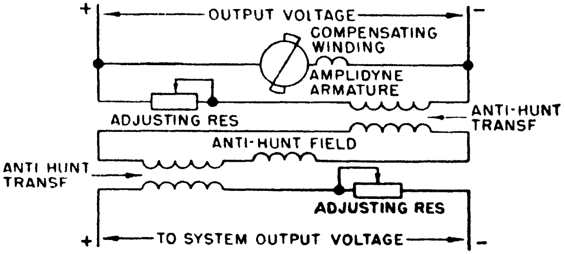
In an amplidyne, a separate anti-hunt field is provided which opposes the action of the control field or fields and derives its excitation from the rate of change of the amplidyne output voltage or from the rate of change of some other system quantity. Shown in Fig. 251 are some commonly used anti-hunt field connections. Only the anti-hunt field is indicated in the sketches, and the control fields are omitted.



A-TRANSFORMER SYSTEM



B-CAPACITOR SYSTEM



C-SPECIAL SYSTEM

Fig. 251. Amplidyne anti-hunt field circuits.

In sketch *A* the primary winding of an anti-hunt transformer which resembles the stabilizer of a voltage regulator is connected to the output terminals of the amplidyne armature. The anti-hunt field is connected to the secondary winding of the transformer. As long as the output voltage is constant, no voltage is induced in the transformer secondary winding, and no current flows through the anti-hunt field. When the amplidyne output voltage changes, a voltage is induced in the transformer secondary winding which is proportional to the rate of change of the output voltage. Consequently, a current flows through the anti-hunt field, the magnitude of which is proportional to the rate of change of the amplidyne output voltage. The polarity of the anti-hunt field is chosen so that its ampere-turns oppose the ampere-turns of the control field which calls for the change in output voltage. Thus the anti-hunt field opposes too rapid a change in output voltage. An adjusting resistor permits varying the ratio between rate of change of output voltage and ampere-turns of the anti-hunt field.

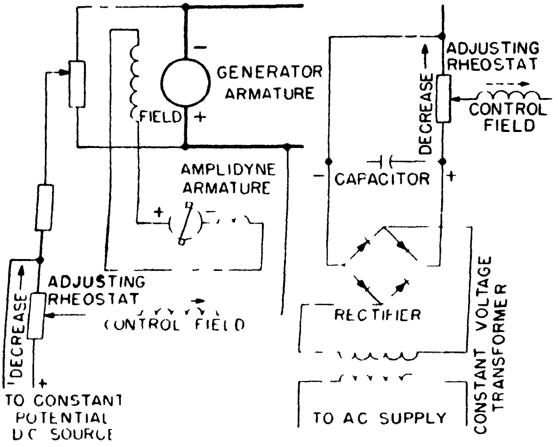
In sketch *B* the anti-hunt field is connected to the output terminals of the amplidyne armature through a capacitor. With constant output voltage, no current flows through the capacitor. When the output voltage changes, a charging current flows through the capacitor and consequently through the anti-hunt field, which is proportional to the rate of change of output voltage The magnitude of the current through the anti-hunt field and the time constant of the anti-hunt correction can be varied by the adjusting resistor. Electrolytic capacitors are used, as a capacitance of the order of 600 to 1200 microfarads is required to obtained effective anti-hunting.

Circuits *A* and *B* are often used and their electrical performance is equivalent. A limitation of capacitor circuit *B* is the fact that electrolytic capacitors are hard to obtain for voltages above 300 volts, which precludes their use if the amplidyne output can rise above 300 volts.

On highly accurate regulating systems, circuits *A* and *B* may not obtain the proper anti-hunting effect because of the time delay between a change in amplidyne output and its effect on the desired system output or because the phase relation of the anti-hunt signal with respect to the system change may not be correct. If this is the case, an additional current is introduced in the anti-hunt field circuit which is proportional to the rate of change of a system output voltage. An example of such a special anti-hunt circuit is shown in sketch *C*. The anti-hunt field is connected to the secondary winding of a transformer which is connected to the amplidyne output circuit as in sketch *A*. Connected in series with the anti-hunt field is the secondary winding of a second transformer, the primary winding of which is connected to a voltage proportional to a system output quantity. It may be the voltage of a d-c generator, the field of which is excited by the amplidyne; or it may be the voltage of a tachometer, measuring the speed of the motor which is controlled by the amplidyne; or it may be a voltage drop proportional to the armature current of a motor. In some cases the transformer connected to the amplidyne output has been omitted, thus making the anti-hunt field respond only to the rate of change of some system output voltage.

Direct-Current Generator Voltage Control

On adjustable-voltage control systems the amplidyne is used to supply excitation to the d-c generator field, whereas the motor field is usually held at a fixed excitation from a constant potential exciter. Motor speed is controlled by controlling the generator voltage through varying the generator field excitation. When requirements of accuracy of maintaining motor speed are not too exacting, it suffices to regulate the generator voltage and to allow the natural drop of motor speed under load to take place. Thus the control problem consists in devising suitable control means for the amplidyne control field which governs the generator voltage.



A DIRECT CURRENT REFERENCE B ALTERNATING CURRENT REFERENCE

FIG. 252. Single-field d-c generator voltage control circuits.

Refer to Fig. 252, sketch *A*. Impressed on the amplidyne control field is the difference in voltage between a constant reference voltage (the standard) and the actual generator voltage. This difference produces sufficient current through the control field to maintain the generator voltage. With polarities as indicated, current flows through the control field in the direction of the arrow.

The standard, also called the reference, is taken from a constant potential source of direct current. The magnitude of the standard can be varied by the adjusting rheostat which permits a portion of the constant d-c voltage to be applied to the regulating circuit. A voltage signal which is directly proportional to the generator voltage is taken off a potentiometer connected across the generator terminals. This voltage is fed into the regulating circuit with such a polarity that it opposes the reference voltage. Suppose that the generator operates at a certain voltage level, corresponding to the setting of the adjusting rheostat. If the generator voltage increases, it overbalances the reference voltage, and the current through the control field is reduced, which in turn reduces the generator excitation. Likewise, when the generator voltage drops, the voltage signal is overbalanced by the reference voltage, the current through the control field is increased, which increases the generator field excitation. Thus the amplidyne regulates the generator voltage and the accuracy is determined by the differential between generator voltage and reference voltage which is required to maintain current flow through the control field.

Control of generator voltage, that is, change in generator voltage level, is obtained by the adjusting rheostat. Turning the rheostat in the direction of the arrow reduces the reference voltage. Current through the control field is reduced, and may even be reversed, until the generator voltage has dropped sufficiently to establish a new balance. Likewise, if the rheostat is turned in the opposite direction, the reference voltage overbalances the generator voltage signal, the current through the control field is increased, and the generator voltage rises until a new balance point is reached.

Forcing is inherent in this control system. When the adjusting rheostat is turned from one voltage setting to another, the current through the control field is increased to several times its normal value, as the differential voltage producing the field current is several times its normal value. It means that the change in amplidyne voltage becomes several times the voltage change required to bring about the change in generator field excitation from one level to another level. The time required to effect a generator field change, corresponding to the desired generator voltage change, can thus be reduced effectively.

It is not always possible to use a constant potential d-c source as a reference. There may be reasons why it is undesirable to tie one side of an exciter to the generator circuit. In practically all plants, an a-c supply system is available, the voltage of which is fairly constant. Sketch *B* indicates how a rectified a-c voltage can be used as a reference voltage. To compensate for possible variations in line voltage, a constant voltage transformer holds the voltage across the rectifier constant. A capacitor is included to smooth the rectifier output voltage.

One side of the adjusting rheostat is tied to the generator armature circuit and is thus subjected to generator potential to ground. When generators with a high terminal voltage are involved, say above 300 volts, this may be objectionable from the point of view of safety. The tie between the generator armature and the control circuit can be avoided by the use of two control fields which buck each other.

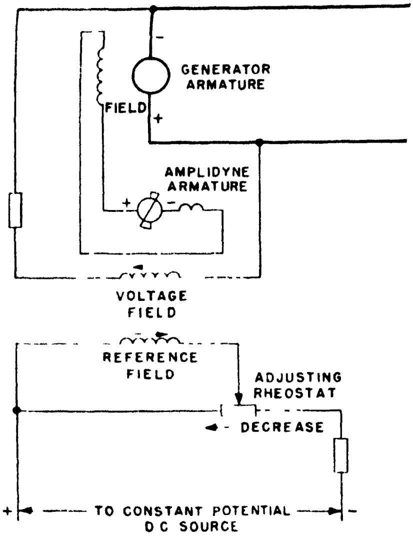


Fig. 253. Two-field d-c generator voltage control circuits.

Refer to Fig. 253. The reference field which establishes the standard is connected to a constant potential d-c source. Either a constant potential exciter or a rectifier and constant voltage transformer can be used as a reference source. The current and the ampere-turns of the reference field are a fixed quantity which can be varied by the adjusting rheostat. A voltage field is connected across the generator terminals. Its current and ampere-turns are proportional to generator voltage. The polarities are chosen so that the reference field and the voltage field oppose or buck each other. The amplidyne armature voltage is thus proportional to the net differential between reference voltage and generator voltage.

Any departure of generator voltage from the set value causes a change in the net excitation of the amplidyne which brings about a corrective action by a change in generator field excitation. The polarity of the generator is determined by the direction of current in the reference field. Upon starting, or when changing the adjusting rheostat setting, forcing takes place automatically, as the differential in ampere-turns between reference field and voltage field becomes a multiple of its normal value, until the voltage field establishes a balance.

The two-field control circuits can be modified in such a way that the reference field is held constant and the adjusting rheostat is connected in series with the voltage field. The adjusting circuit is then connected to the generator armature circuit, which makes such a circuit undesirable for high-voltage generators.

Current Control

Control of armature current is required when adjustable-speed shunt motors are used to drive winding or unwinding reels. While the diameter of the reel changes, it is necessary to adjust the motor field excitation so as to keep its armature current constant, which in turn means that the tension on the material being reeled is kept constant. In this case, the amplidyne is used as a current regulator.

Shown in Fig. 254 is a simple amplidyne current regulator for a shunt motor, operating from a constant or adjustable d-c voltage source. The amplidyne armature is connected in series with the motor shunt field. The amplidyne has two control fields. The reference field is connected to a constant potential d-c source and provides a fixed amount of ampere-turns. The current field is connected across a resistor in series with the motor armature. The voltage drop across that resistor is a measure of the motor armature current. Thus the ampere-turns supplied by the current field are proportional to the motor armature current.

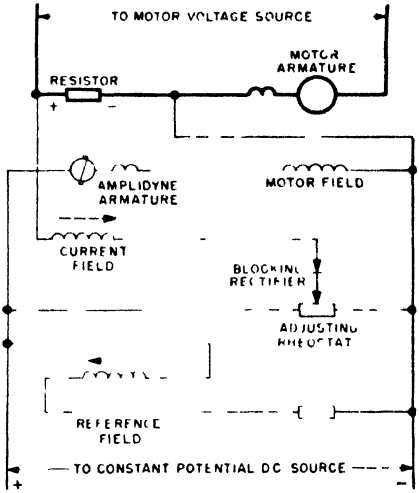


Fig. 254 Motor current control circuits.

The net excitation of the amplidyne, which governs direction and magnitude of the amplidyne voltage, is the difference in ampere-turns between the current and the reference field. With only the reference field excited, the direction of the amplidyne voltage is such as to oppose the voltage across the motor field circuit, thus calling for maximum weakening of the motor field. At the beginning of the winding cycle, motor speed is high. As tension is picked up, the motor current increases, increasing the voltage drop across the resistor in series with the motor armature. When this drop exceeds the voltage against which it is balanced by the adjusting rheostat, current begins to flow through the current field, which opposes the reference field. As the motor armature current increases, the amplidyne voltage decreases, and may even reverse, strengthening the motor shunt field and reducing the motor speed. Likewise, when the motor armature current drops below the set value, the effect of the current field is reduced, the motor field is weakened, and the motor speed is increased.

Current Limit Control

During acceleration and deceleration of a drive between speed levels, it is important that the motor and generator armature current *shall not exceed the commutating* limit of the machines. Current limit control of an adjustable-voltage system prevents the current in the loop circuit between generator and motor from rising beyond a predetermined value. As compared with current control, current limit control takes effect only when the current tends to exceed the limit value, whereas the control is inoperative as long as the current stays below the limit value.

Current limit control is used in conjunction with generator voltage or speed control. If during acceleration the loop circuit current exceeds the set limit, the generator field is weakened to prevent too rapid a rise in generator voltage. On the other hand, if the loop circuit current exceeds the set limit during deceleration, the generator field is strengthened to prevent too rapid a decay of generator voltage. Either a separate current limit control field may be used, or current limit control may be superimposed on the voltage or speed control field.

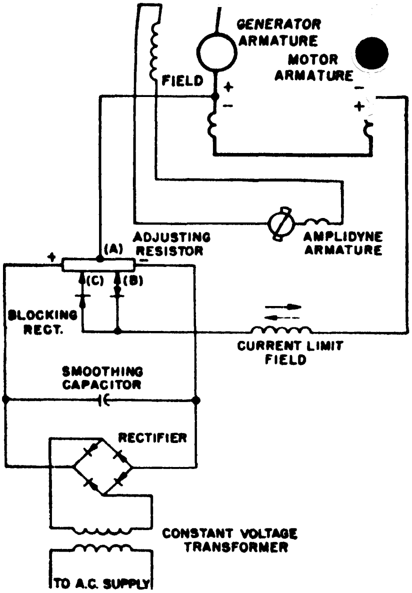


FIG. 255. Current limit control circuit with separate current limit field.

Shown in Fig. 255 is a current limit control circuit, using a separate current limit field. The commutating fields of the generator and the motor are connected in series, and the voltage drop across the commutating fields is used as a measure of the loop circuit current. If the commutating field resistance is too low to obtain a sufficiently high drop, a loading resistor may be added in the loop circuit. A reference voltage is obtained from either a constant voltage d-c source or from an a-c source through a constant voltage transformer and rectifier. The reference voltage is loaded into the adjusting resistor. The mid-point *A* of this resistor is connected to the generator armature. Adjustable taps *B* and *C* on either side of the mid-tap are connected through blocking rectifiers to one side of the current limit field. The other side of this field is connected to the motor armature.

Suppose that during acceleration the polarity of the loop circuit is such as is indicated by the solid plus and minus signs. As long as the drop across the commutating fields is less than the drop between *A* and *B* on the adjusting resistor, no current flows through the current limit field. As soon as the loop circuit current rises to such a value that the voltage drop across the commutating fields becomes greater than the drop between points *A* and *B*, current flows through the current field in the direction of the solid arrow. The polarity of that field is such as to oppose the rise in amplidyne armature voltage, thus delaying the build-up in generator field excitation.

During deceleration, the direction of the loop circuit current reverses and the polarity of the loop circuit is as indicated by the broken plus and minus signs. When the voltage drop across the commutating fields exceeds the drop between points *C* and *A*, current flows through the current limit field in the direction of the broken arrow. The effect is to oppose the reduction in amplidyne armature voltage and thus the decay in generator field excitation. By shifting taps *B* and *C* on the adjusting rheostat, a different current limit setting can be obtained for acceleration and deceleration.

Figure 256 illustrates a method of superimposing current limit control on a voltage control field. A constant voltage d-c source is used as a reference. Voltage control is obtained by matching a reference voltage between the adjustable tap of the voltage-adjusting rheostat and point *A* against the drop across part of the voltage resistor, into which the generator voltage is loaded. The current through the control field is determined by the net difference between reference voltage and generator voltage. For polarity as indicated by solid plus and minus signs, current flows through the control field in the direction of the solid arrow.

Current limit control is obtained by superimposing on the control field the net difference between the drop across the generator and motor commutating fields and the reference drop across the current-limiting resistor. The control field current, due to the current limit component, is indicated by broken arrows. During acceleration, polarity across the commutating fields is as indicated by solid signs, and the drop between *A* and *B* governs. Current limit control opposes the effect of voltage control and opposes the build-up of amplidyne armature voltage. During deceleration, the polarity across the commutating fields is as indicated by broken signs. The drop between points *C* and *A* governs the current limit, and the current limit component of current through the control field adds to the current due to voltage control. Thus the amplidyne net excitation is strengthened and the decay of generator armature voltage is opposed.

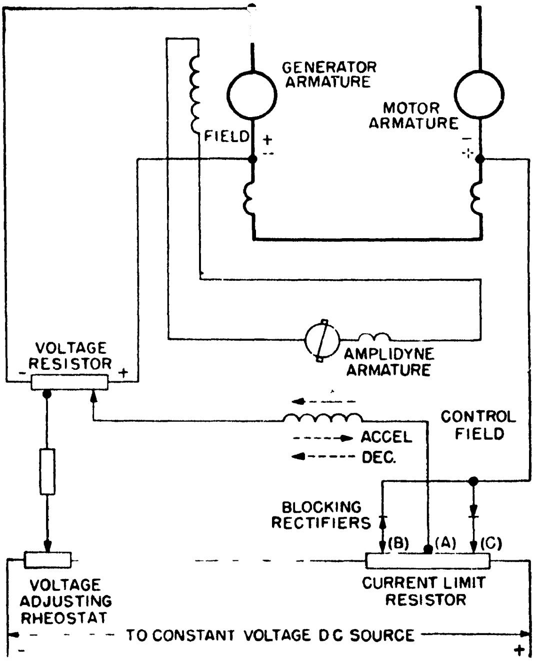


FIG. 256. Current limit control circuit superimposed on generator voltage control field.

Reversing Plugging Control

In a complete controller, several control elements, as described in the preceding paragraphs, are combined into a complete system. As an example, the essential elements of a reversing plugging controller are indicated in Fig. 257. The amplidyne, which excites the field of the generator, is equipped with four control fields, the net ampere-turns of which determine the total excitation and thus the terminal voltage of the amplidyne. It is assumed that the motor field is excited from a constant voltage source. A master switch, which controls contactors *F* and *R*, is used to select direction of motor rotation. Positive polarity of the generator is marked for both directions of rotation.

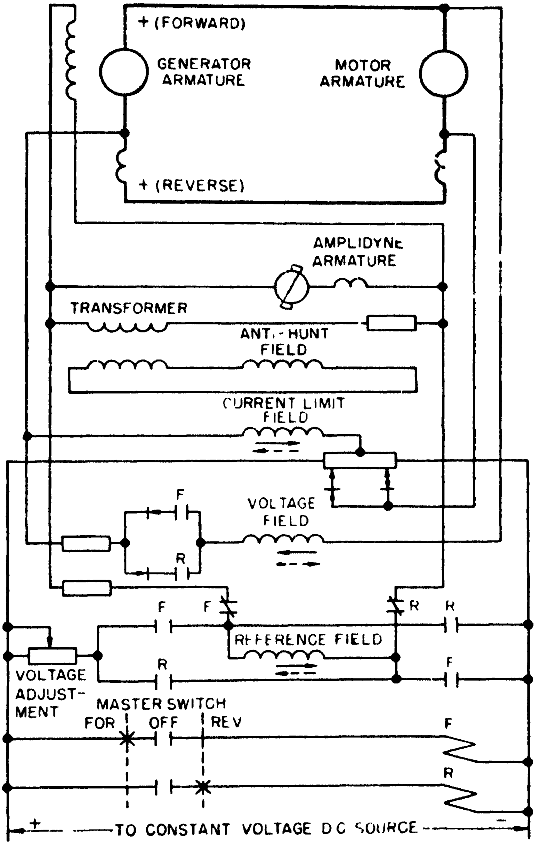


FIG. 257. Reversing plugging control circuits. *F*. Forward contactor. *R*. Reverse contactor.

Direction of current flow through the control fields is indicated by solid arrows for forward travel, and by broken arrows for reverse travel.

The reference field is connected to a constant voltage d-c source through reversing contactors *F* and *R*. The magnitude of the reference field current establishes the standard for the generator voltage. The direction of the field current determines the polarity of the amplidyne and consequently the polarity of the generator. The motor is reversed by reversing the reference field. With the master switch in the "off" position, the reference field is connected to the amplidyne armature through normally closed contacts on contactors *F* and *R* with such a polarity as to oppose the excitation which is producing the amplidyne output voltage. This connection establishes a neutralizing or "suiciding" circuit to reduce the residual magnetism in the reference field to zero, which in turn reduces the amplidyne terminal voltage to zero when the drive is stopped. The generator voltage is regulated by the voltage field, which is connected to the generator armature in such a direction as to buck the reference field. To obtain correct flow of current through the voltage field during plugging, contacts on *F* and *R* as well as blocking rectifiers are connected in series with the field.

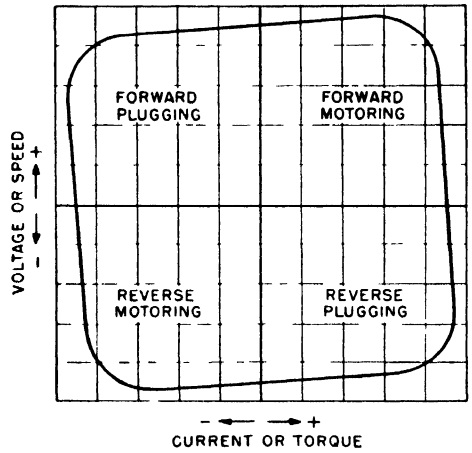


FIG. 258. Envelope of performance of a reversing plugging control system.

The current limit field is connected so that its current is determined by the net difference between the voltage drop across the generator and motor commutating fields and a constant reference voltage drop. During acceleration, as well as during plugging, the current limit field prevents excessive build-up of generator armature current, and thus limits the motor torque. In Fig. 258 the volt-ampere characteristic of the generator, which corresponds to the speed-torque characteristic of the motor, is shown. The curve applies to a certain setting of voltage and current limit control. It is representative of the kind of characteristic that can be obtained with amplidyne control. Changes in details of the control circuits may vary the shape of the curve somewhat, especially the slope of the current limit cut-off.

Varying the amount of resistance in series with the reference or control field changes the horizontal portions of the curve. The curve as shown represents a boundary condition, and inside the loop any speed-torque point can be realized by proper adjustment of the voltage control.

An anti-hunt field stabilizes the amplidyne. Transformer stabilizing is shown as an example, but either capacitor or special anti-hunt connections could be used.

The circuit of Fig. 257 is indicative of the manner in which various circuit elements are combined into an integrated control system. Many combinations are possible and practical. Conversely, any complicated control system can be broken down into a series of simple circuits, superimposed on each other to obtain the desired control effect, and each field responding to a definite signal or combination of signals obtained from the system.

Speed Control

In the preceding paragraphs control connections are described by which electrical quantities, such as generator voltage or current, are regulated. Certain applications require that motor speed itself be regulated in order to compensate for the natural drop in motor speed with increase in load. It requires that a signal be fed into the regulating circuit which is a direct function of motor speed. Customarily, a tachometer generator is coupled to the motor. This tachometer produces a d-c voltage proportional to speed.

A simple speed control circuit is shown in Fig. 259. The output voltage of the tachometer is loaded into a resistor, and a portion of the voltage drop across that resistor is used as the speed signal. The reference is obtained from a constant potential d-c source. A portion of the d-c voltage is used as the standard against which the speed signal is balanced. The current through the amplidyne control field is proportional to the net difference between the reference voltage and the tachometer voltage. Direction of the control field current is indicated by the arrow. The speed of the motor is set by the adjusting rheostat, by means of which the magnitude of the reference voltage is varied.

Speed control may be superimposed on a conventional generator voltage control circuit to obtain increased accuracy. The voltage control is adjusted so that, by itself, it would produce a higher amplidyne voltage than is required for the desired motor speed. The separate speed control field then reduces the net excitation of the amplidyne so as to maintain the generator voltage at the required values to obtain constant motor speed.

Some applications require that a definite speed relationship be maintained between two motors in a process line. Each of the two motors is then equipped with a tachometer generator, and the difference in voltage between the two tachometers is used as a signal. One motor is the master, whose speed is controlled by the operator. The second motor is the follower, and its amplidyne is provided with a speed control field, which responds to the difference in tachometer voltages and thus corrects for any deviation in the speed of the follower motor from the speed of the master motor.

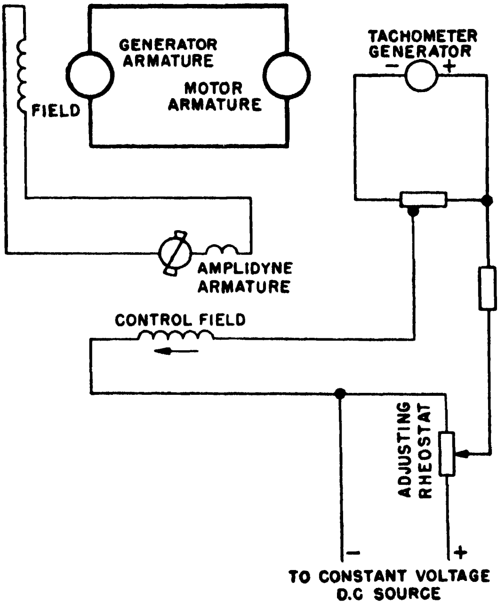


FIG. 259 Speed control circuits.

The error obtainable with a speed-regulating system depends on the error of the tachometer and on the minimum deviation of tachometer voltage to which the regulator responds. The error can be reduced by using an electronic amplifier to magnify the speed signal which is fed into the amplidyne control field circuit.

Positioning Control

Amplidynes can be used to maintain a mechanical part in a definite position as a function of one or more quantities which can be translated into electrical signals. The amplidyne is then used as an adjustable-voltage generator feeding the armature of a shunt motor, the field of which is excited from a constant voltage source. The positioning signal may be obtained from a variable voltage source, such as a selsyn, which is turned by hand. This method is used to control amplidynes forming part of a servo-mechanism. Or the positioning signal may be obtained from some electrical quantity of the system. A typical example is the arc furnace electrode regulator, the essential control circuits of which are shown in Fig. 260.[6]

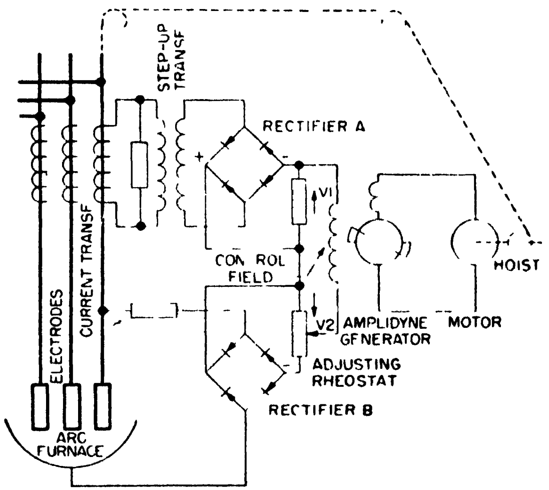


FIG. 260. Positioning control circuits for arc furnace electrodes.

An arc furnace contains three electrodes, one for each phase, from which current passes into the charge through an arc. The object of the control is to maintain each electrode automatically in such a position as to obtain constant power flow through each electrode. Constant power is maintained by maintaining constant arc current with relation to the arc voltage. The height of each electrode over the charge is varied individually by a motor-driven hoist. In Fig. 260 the control circuits for one electrode are indicated. The circuits for the other two electrodes are duplicates.

The arc current is measured by a current transformer. The voltage appearing across the current transformer secondary winding, which is proportional to arc current, is applied to the primary winding of a step-up transformer. The output voltage of this transformer is impressed on rectifier *A*, and the resultant d-c voltage is loaded into a resistor. The voltage drop *V*1 across that resistor is proportional to the arc current and provides the signal for the amplidyne.

The arc voltage, appearing between the electrode and the neutral point of the furnace, is used as a reference. The arc voltage is rectified by rectifier *B*, and the d-c voltage which is proportional to arc voltage is loaded into the adjusting rheostat. This rheostat is connected as a potentiometer, and across a portion of it appears a voltage *V*2 which is proportional to arc voltage and opposes voltage *V*1.

The control field of the amplidyne generator is so connected that its field current is proportional to the net difference between voltages *V*1 and *V*2. As long as *V*1 and *V*2 are of equal magnitude, no current flows through the amplidyne field and the amplidyne output voltage is zero. The electrode motor is at standstill, and the electrode is at rest. If the electrode current changes and the balance between voltages *V*1 and *V*2 is disturbed, current flows through the control field and the amplidyne generates an output voltage, the polarity of which depends on whether *V*1 becomes larger or smaller than *V*2. This unbalance between *V*1 and *V*2 causes the electrode motor to turn in a direction to raise or to lower the electrode, until a balance is established again. As the speed of the motor is proportional to the difference between *V*1 and *V*2, the electrode is moved smoothly, and without overshoot, into a new position at which the current is equal to the set value.

The same principle is used in photoelectric register controls. Two photoelectric relays scan the edges of a moving strip of material, and the output currents of the phototubes are used for a signal. As long as the strip is in register, the photoelectric tubes receive equal amounts of light, and the amplidyne generator field carries no current. As soon as the strip gets out of register, one phototube receives more light than the other, and the difference in phototube currents causes current to flow through the amplidyne field, which in turn causes a correction motor to move the strip back into the register position. Because of the low amount of energy available from the phototubes, it is necessary to interpose an electronic amplifier between the phototube circuit and the amplidyne field circuit.

Alternator Voltage Control[8]

Certain industrial processes use alternating current, obtained from an alternator, the voltage of which must be closely regulated to insure uniform quality to the product. An example are alternators for high-frequency induction heating. The essential circuits of an alternator voltage control system are shown in Fig. 261.

The alternator field is excited by an amplidyne generator which is stabilized by a conventional anti-hunt field, connected to the amplidyne armature through a capacitor. A voltage field determines the excitation of the amplidyne which maintains the desired alternator voltage. The voltage field current is proportional to the net difference between a reference voltage and a voltage signal. The reference voltage is obtained from a constant voltage d-c source. In the circuit shown, reference voltage is obtained from an available a-c source through a constant voltage transformer. The reference voltage is rectified by rectifier *B* and loaded into a potentiometer which serves as an adjusting rheostat. A portion of the reference voltage is impressed on the voltage field.

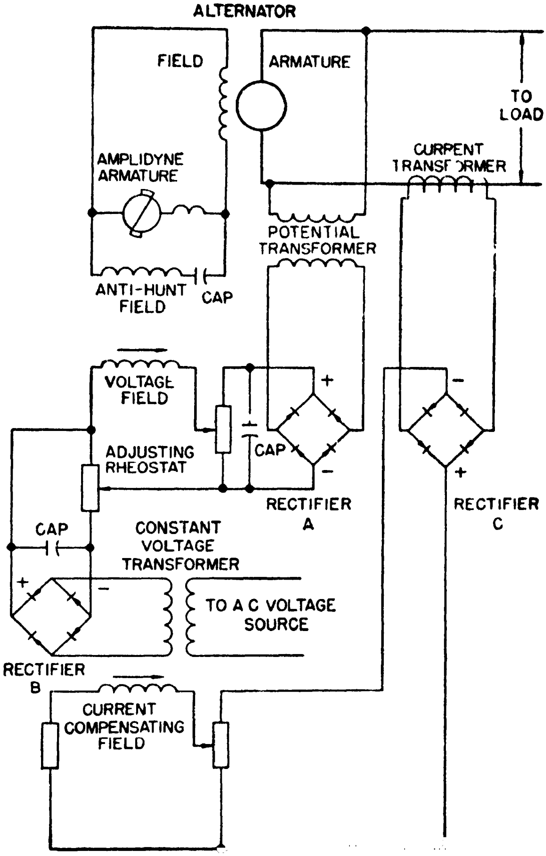


Fig. 261. Alternator voltage control circuits.

The voltage signal is obtained from the alternator armature through a potential transformer. The voltage signal is rectified through rectifier *A* and loaded into a resistor. A portion of the drop across the resistor is applied to the voltage field. Polarity is such that the voltage signal, which is proportional to alternator voltage, opposes the reference voltage. When the reference voltage is applied to the voltage field, the alternator voltage rises to such a value that the net excitation of the amplidyne maintains the alternator voltage. A rise in alternator voltage results in a reduction in amplidyne voltage, and a drop in alternator voltage results in a rise in amplidyne voltage. The level of alternator voltage which is to be maintained is varied by the adjusting rheostat, which changes the magnitude of the reference voltage impressed on the voltage field.

To maintain voltage across the load and compensate for line drop, a current compensating field is used which corrects the alternator voltage. A current transformer is connected in the line between the alternator and the load. The secondary voltage of this transformer is proportional to line current. The secondary voltage is rectified, loaded into a resistor, and applied to the current compensating field of the amplidyne. Polarity is such that with increasing current, the compensating field boosts the amplidyne voltage and raises the alternator voltage somewhat above the voltage called for by the adjusting rheostat, thus maintaining constant voltage across the load.

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CHAPTER 14

PROTECTION

Although the principal purpose of a controller is to obtain specific performance, such as starting, regulation of speed, deceleration, and the like, it is necessary to include provisions to protect both the operator and the equipment against damage by normal or abnormal operating conditions. The protective features which should be included in control equipment can be classified as follows:

1. Protection of operators against shock by proper insulation and spacing of live parts.
2. Protection of operators against false starts or inadvertent motor reversal, or excessive motor speed.
3. Protection of motors against sustained overloads.
4. Protection of motors and driven machinery against sudden overloads.
5. Protection of control equipment against short circuits.

Because of the importance of safety, it has been deemed proper to devote a whole chapter to a discussion of the selection of proper protective features in the design and construction of control equipment. It should be kept in mind that protection of distribution lines and generating equipment is outside the province of control and belongs to the scope of switchgear. Only such phenomena as occur between the line terminals of the controller and the motor terminals are of interest to the control designer.

Minimum Spacing [1]

To provide proper insulation between current-carrying parts and between current-carrying parts and ground is a requirement which is necessitated not only by engineering considerations but also by safety rules. It must be assumed that an operator may touch any part not carrying current, and he must be safeguarded against the possibility of receiving a shock. To prescribe only a high-potential test at the factory would not assure safety in service. At the installation, dust and dirt will accumulate on insulating surfaces and reduce the voltage which the insulation can stand.

The Underwriters' Laboratories, Inc., have established minimum spacings which must be met by general-purpose control devices as used in industry. These spacings, which are given in Table 17, have been established through years of experience. They are graded according to voltage levels, and they give reasonable assurance against shock to operators.

TABLE 17

MINIMUM SPACINGS AS SPECIFIED BY UNDERWRITERS' LABORATORIES

		51 to 150 Volts	151 to 300 Volts	301 to 600 Volts
Between any uninsulated live part and an uninsulated live part of opposite polarity, uninsulated grounded part other than the enclosure, or exposed metal part.	Through air or oil	⅛ inch *	¼ inch	⅜ inch
	Over surface	¼ inch	⅜ inch	½ inch
Between any uninsulated live part and the walls of a metal enclosure, including fittings for conduit or armored cable.*	Shortest distance	½ inch	½ inch	½ inch

* The spacing between wiring terminals of opposite polarity shall not be less than ¼ inch in any case if the terminals are in the same plane. A metal piece attached to the enclosure shall be considered to be a part of the enclosure for the purpose of this paragraph, if deformation of the enclosure is likely to reduce spacings between the metal piece and live parts.

As an additional safety feature, non-current-carrying metal parts of manually operated pilot devices, enclosures, frameworks, etc., should be grounded.

Undervoltage and Phase Reversal Protection

It is extremely important to prevent inadvertent starting of any motor which is under the control of an operator. Once a motor has been stopped, either by action of the operator or by action of a protective device or by loss of voltage, the motor must not start automatically, but the operator must actuate a pilot device to restart the motor. Therefore, any manually operated magnetic control equipment should include undervoltage protection. In Chapters 11 and 12, it is pointed out that controllers with momentary push buttons provide undervoltage protection inherently. Master-switch-operated controllers should include an undervoltage relay which forces the operator to return the master switch to the off position for resetting the undervoltage relay. The contacts of protective devices are connected in series with the undervoltage relay coil, causing the motor to stop when any protective device opens and trips the undervoltage relay.

Undervoltage protection is not required when motors are under automatic control of maintained contact pilot devices, such as float switches, pressure switches, thermostats, or similar devices, which respond to conditions in the plant to be controlled. Such plants are not attended by operators, and an automatic start after loss of control voltage falls in the same category as a regular automatic start, as far as safety to personnel is concerned.

To what extent safety interlocking should be included in complicated control equipments involving sequencing of a multiplicity of motors depends largely on the character of the drive and the hazards which a false start would entail. It is necessary, however, to scrutinize the design of a controller carefully and to determine to what extent a failure of safety interlocking may endanger the operator. Control devices, like any piece of machinery, may fail to perform their functions properly, the most common causes of false operation being coil failure and freezing of contacts of magnetic devices. Little can be done in the design of control circuits to safeguard against contacts sticking closed. Any control system should include manually operated switches with which power circuits can be interrupted and motors stopped in an emergency, should line contactors fail to open the power circuit. Failure of contactor or relay coils can be guarded against by arranging the circuits so that any coil failure will cause stopping rather than starting of a motor. Such circuits are called "fail safe" circuits.

Reversal of the phase sequence of a polyphase system is equivalent to reversing a motor, and rotation of the motor would be opposite to the desired rotation. If inadvertent reversal of a machine may cause danger to life and limb of operating personnel, a reverse phase relay of a type as shown in Figs. 129 and 130 must be provided to prevent the motor from running when the phase sequence is incorrect. Machinery used for transporting persons, for instance elevators, must be protected with phase reversal relays.

Loss of Field Protection

When the field circuit of a d-c shunt motor is interrupted, the remaining residual flux permits the motor to develop a small fraction of its full-load torque, but its speed may rise to a dangerously high value. If the drive is of such a nature that the motor can never be unloaded, no protection against loss of field is necessary, since the motor torque would be too small and the drive would stall. However, if the motor may be unloaded or even overhauled—for instance when the motor drives a hoist or a motor generator set—it is very important to include a loss of field or field failure relay. A current relay is used, the coil of which is connected in series with the shunt field winding and the contact of which is wired in series with the undervoltage relay coil.

Overload Protection

An overload on a motor can be defined as an operating condition, not necessarily a short circuit, which causes a current in excess of normal current to flow in the motor power circuit. Thus overload protection is defined as the protection of the motor, the control apparatus, and the branch circuit conductors against excessive heating due to motor overload. It can be further defined as the effect of a device, responsive to current, to cause interruption of current flow to the motor operating under an overload.

The damaging effect which an overload may have on the connected apparatus is due to the excessive temperature which the increased current flow causes the apparatus to attain. This rise in temperature introduces two more quantities, in addition to the magnitude of current, which must be considered in designing and applying protective devices, namely, the time during which the overload exists and the ambient temperature. In an extreme case, the temperature may rise so high as to cause melting of conductors, and thus cause permanent damage to the motor, the control apparatus, or the circuit conductors. But even if the temperature does not rise so high as that, any increase in temperature above rated temperature rise reduces the life of the insulation and results in shortened life of the motor.

The most commonly encountered causes of overload on a motor are:

1. Sustained overload caused by abnormal mechanical load or by low line voltage.
2. Too rapid duty cycles on intermittent drives, such as too frequent starting and stopping, which cause the rms value of current to exceed the rated motor current.
3. Excessive mechanical load, which causes the motor to stall or fail to start, thus drawing starting current for a considerable period of time.
4. Single phasing of polyphase motors, preventing the motor from starting or causing excessive current to flow while the motor runs.

5. High ambient temperature, which causes the motor to attain higher than rated temperature even though the load current stays within the motor rating.

To afford full protection to a motor, the tripping characteristic of the overload protective device should match the motor heating characteristic. To obtain the highest degree of service from the motor, the overload relay should permit the motor to carry an overload for as long a time as is necessary for the motor to reach its maximum permissible temperature, but it should disconnect the motor as soon as that temperature is reached. Any overload protective device should thus have an inverse time tripping curve, which should follow the motor-heating curve as closely as possible. Unfortunately, heating curves for electric motors are not standardized, and considerable differences may exist between motors of the same horsepower rating but of different manufacture. A typical heating curve for an induction motor is plotted in Fig. 262. The time in seconds necessary for the motor to reach maximum permissible temperature is plotted versus current in per unit.

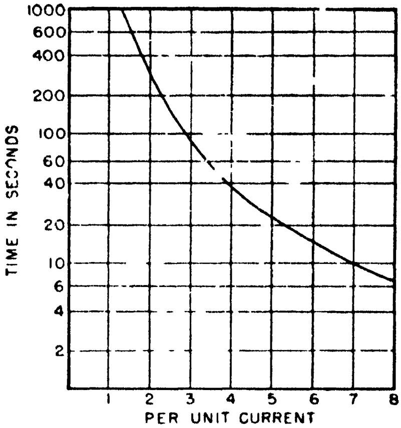


FIG. 262. Typical heating curve of an induction motor.

Because of the variations in motor heating curves, any design of commercial overload relays must necessarily be a compromise, and the tripping characteristics of such relays must be selected so as to protect a majority of commercial motors. Unusual service conditions necessitate a special check of motor heating versus relay tripping characteristic. Especially if stalled motor protection is desired, great care must be exercised in selecting overload relays, since a relay which protects the motor perfectly satisfactorily at moderate overloads may still be too sluggish to protect the motor under a stalled condition.

Overload Relays—General

Before describing the various types of overload relays available for motor protection, some points will be discussed which apply generally to any type of protective relay.

Overload relays consist of a current-carrying conductor such as a coil or a heater, through which line current flows, and a contact which is actuated by the coil. A coil may operate the contact by magnetic force. Instantaneous and most inverse time overload relays work on this principle. Or a coil or a heater may cause a temperature-sensitive element, such as a strip of bimetal, to heat and deflect, tripping the contact mechanically. Such relays are called thermal overload relays.

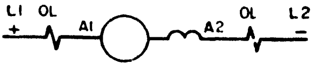
Most overload relays used for industrial control work have normally closed contacts, that is, the contacts are closed with no current flowing, and the contacts open when an overload current flows through the relay. Contactors used on magnetic controllers are generally closed by holding their coil energized. Overload protection is obtained by the overload relay contacts interrupting the line contactor coil circuits, causing the line contactors to drop out and to disconnect the motors from the line. Contrary to control practice, switchgear practice prefers mechanically latched-in circuit breakers. A trip coil, energized on overload, causes the breaker to open. Thus overload relays used on switchgear generally have normally open contacts which close and energize the trip coil upon occurrence of an overload.

Contacts of overload relays may be self-reset or hand-reset. On self-reset relays, the contact recloses automatically after the motor has been disconnected from the line. On hand-reset relays the contact stays open until it is reclosed mechanically, usually by pressing a reset button. On magnetic controllers using momentary contact pilot devices or master switches with undervoltage protection, either type can be used. Although the hand-reset feature is not necessary to obtain satisfactory operation, many control users prefer hand-reset overload relays because the operator is forced to go to the control panel to reset the relays. This manual operation prevents the operator from restarting his drive immediately upon an overload, and there is a greater probability that the operator will investigate the cause of the overload. Hand-reset overload relays must be used on controllers with maintained contact pilot devices, as self-reset relays would cause the motor to "pump," that is, the motor would continually attempt to restart against the overload.

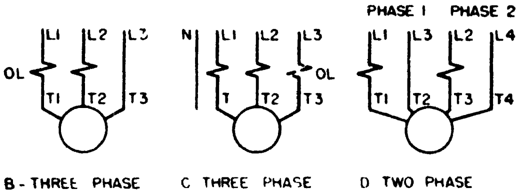
The question arises of how many relays should be used and how they should be connected in the motor circuit. The connections of overload relay coils in the most commonly used motor circuits are indicated in Fig. 263. See sketch A. Overload relays for d-c motors are connected in the lines to the motor armature. Relays which protect against short circuits are connected in both sides of the line.

Relays which protect against operating overloads need be connected in only one side of the line, preferably the positive side, since the negative line is grounded on many industrial systems.

Three-phase induction motors are protected by overload relays in two phases, as indicated in sketch *B*, both against short circuit and against overload. If the motor is connected to a four-wire network system, overload protective relays in two phases are sufficient, as the neutral wire has no effect on the balanced load current of the motor. However, if relays are to protect against winding faults or short circuits, any one of the three phases may short-circuit to ground, and three relays, one in each phase, are required, as shown in sketch *C*. Two-phase motors are protected against overload and short circuit by two relays, one in each phase (see sketch *D*).



A DC MOTOR



B - THREE PHASE MOTOR ON THREE WIRE SYSTEM

C THREE PHASE MOTOR ON FOUR WIRE SYSTEM

D TWO PHASE MOTOR

FIG. 263. Connections of overload relays in motor circuits.

When selecting the size of overload relay to protect a given motor, its service factor must be considered. Standard continuous-rated motors for 40 C rise have a service factor of 15 per cent, that is, the motor can deliver 15 per cent more power than its nameplate rating indicates without injurious heating, and relays should be selected for a current of 115 per cent motor full-load current.

Thermal Overload Relays [2, 3]

This type of overload relay, which has found universal use for the protection of continuously rated motors, uses the heat-storing ability of a thermal responsive element and connected mass. The heat generated by the motor load current flowing through the relay is conducted, convected, or radiated to this element, which causes the relay contact to open when it has reached a certain temperature.

By proper design of the relay parts, and by providing the necessary heat-storing capacity, the heating characteristic of the relay can be made to follow closely the heating characteristic of the motor. The tripping characteristic, that is, the tripping time plotted versus current, should simulate the motor-heating curve as shown in Fig. 262.

Classified on the basis of the temperature-responsive element used, the following groups of relays are commercially available:

1. Solder pot or solder film type.
2. Direct expansion type.
3. Bimetal type.

Solder pot and soder film relays utilize an alloy with a low melting point. When the relay reaches the temperature for which it is designed, the solder softens sufficiently to release a spring mechanism, opening the relay contact. After the solder has had time to harden, the relay can be reset. Such relays are inexpensive, but great care must be exercised in their manufacture to obtain reliable operation. They are used mostly on manual and magnetic starters for small induction motors.

Direct expansion relays make use of the elongation of a piece of metal under the effect of heating, and this expansion, suitably amplified by a lever system, actuates the contact. Although this principle has found considerable application in the design of thermostats, it has not been used widely for overload relays, although it presents interesting possibilities for future development work.

Bimetal relays are the most commonly used types of thermal relays. The heat-responsive element is a strip of bimetal which is deflected by heat. To eliminate variations in the tripping point, the deflection of the strip does not actuate the contacts directly, but the strip releases a mechanical latch, permitting a spring to open the contact. Thus the mechanical work which the bimetal strip has to perform is kept at a minimum, insuring uniform tripping. After the relay has tripped, a definite period of time must elapse before the bimetal strip returns close enough to its original position to permit the relay to be reset.

Resistance type thermal relays contain a resistor through which load current flows. The heat generated in the resistor element is radiated, and to a limited extent conducted and convected, to the bimetal strip. Figure 264 shows a relay of this type suitable for use with d-c or a-c motors. The bimetal strip forms a cantilever, arranged inside the resistance element. When the strip is deflected sufficiently, a trip lever is released upward, causing a horizontal bar to turn and to open the relay contact. By interchanging heaters of various sizes the relay can be used for motors of different full-load currents. One, two, or three bimetallic elements can be arranged on one relay, all elements actuating the same contact. After the bimetal strips have cooled sufficiently, the reset button may be pressed, which turns the horizontal bar and pushes the trip levers downward so that they engage again with the bimetal strips.

In sketch *B* the average times required to trip and to reset the relay in a 40 C ambient are plotted versus per unit motor current. A comparison with the motor-heating curve of Fig. 262 indicates that for currents up to six times normal the relay trips within a shorter time than that required by the motor to reach its ultimate temperature limit. At higher currents, the relay would not fully protect the motor. Therefore, when thermal overload relays are used with motors having a high stalled current, a careful study must be made of motor heating to determine whether the selected relay affords motor protection during a stall.

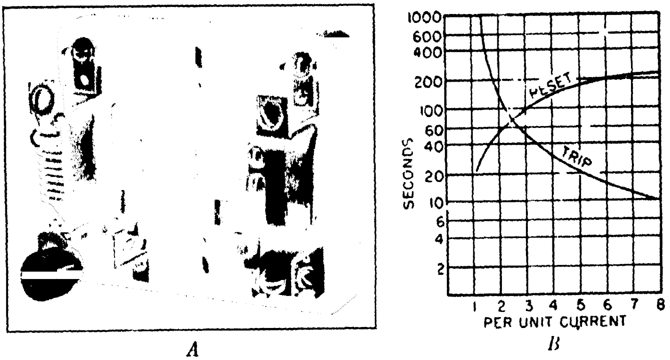


Fig. 264 Resistance type thermal overload relay. *A*. Front view of relay. *B*. Tripping curve.

The resistance heating elements have a limited heat-storage capacity. Since there is a time lag between the heating of the resistance element and the heating of the bimetal strip, the heating element may melt and damage the relay permanently under a heavy short-circuit current before the relay is able to trip. Thermal overload relays do not afford short-circuit protection, and fuses or fast-tripping circuit breakers should always be installed in the lines ahead of the relays. The National Electric Code [1] specifies that the rating of such fuses or circuit breakers shall be not over four times the rated current of the motor.

Another method to get the heat into the bimetal strip is by induction, and a relay based on that principle is shown in Fig. 265. The bimetal strip is arranged inside a copper tube, which is surrounded by the relay coil. The coil acts as the primary, and the copper tube as the single-turn secondary winding of a transformer. Load current flowing through the coil induces a current in the tube, which heats up, and the heat is transmitted to the bimetal strip in the tube. Such relays can be used only with a-c motors. Deflection of the bimetal strip actuates the relay contacts, which are either self-reset or hand-reset by a reset button. This type of relay is available only in a single-pole form, and two relays must be used to protect a three-phase motor. For motors rated above 100 amperes, current transformers are used to supply the relays. The tripping characteristic is similar to the one shown in Fig. 264.

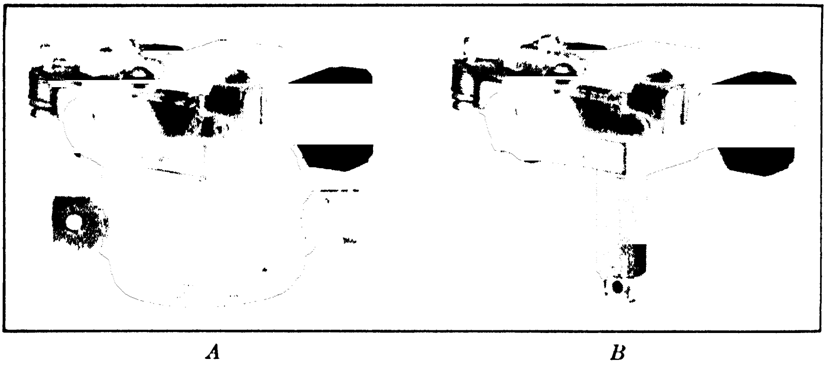


FIG. 265. Induction type thermal overload relay. *A*. With coil assembled. *B*. Less coil.

When thermal overload relays are applied, it must be recognized that these relays are essentially responsive to temperature, and changes in ambient temperature have an effect on the current at which the relays trip. For example, the ultimate tripping point of a thermal overload relay, without any current flowing through its heater or coil, is approximately 95 to 100 C. At that temperature, the bimetallic strip will be at the point of tripping. As long as motor and relay operate in the same ambient temperature, and the motor is applied on the basis of its 40 C ambient rating, the relay automatically compensates for variations in ambient temperature. If the relay operates in a higher ambient temperature, while the motor operates at normal ambient of 40 C, the increase in relay ambient temperature can be accounted for by selecting a larger relay heater or coil, usually one size larger for each 15 C increase in relay ambient temperature above 40 C.

On some control applications the relay is subjected to widely fluctuating ambient temperatures, while the motor operates in normal ambient temperature. For instance, the control may be installed outdoors, while the motor is indoors. Relays are available which are compensated for ambient temperatures. A compensated relay of the induction type, illustrated in Fig. 266, shows the relay exploded so that its internal parts can be seen. The bimetal strip is wound in the form of a helix, which is surrounded by the coil. The coil current induces a current in the helix, which causes the helix to heat, and the resultant rotary motion actuates the relay contact. The tripping current varies approximately 3 per cent for every 10 C change in ambient between 20 and 70 C.

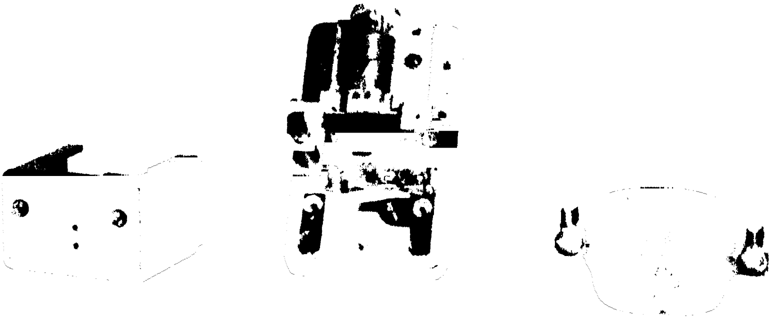


FIG. 266 Induction type thermal overload relay with compensation for ambient temperature

Compensated relays tend to recognize only the circuit flowing through them, without regard to the temperature of the surrounding ambient. Thus when the motor and the controller operate at an ambient temperature above the normal 40 C, a compensated temperature relay will allow current to flow through the motor, just as if it were operating in a normal ambient. As a result, temperature in the motor may be excessive. Judgment must be exercised when applying compensated relays.

For selecting the proper thermal overload relay heater or coil for a given motor application, the relay data published by the manufacturer are used. The standard relay tables are based on general-purpose 40 C rise continuous-rated motors, having a 15 per cent service factor. As commercial motors are usually rated on a conservative basis, and in order to keep the number of heaters and coils of a complete line within reason, the standard relay tables are laid out so that the relay will ultimately trip at a current between 110 and 130 per cent of motor full-load current. Such tables are based on peacetime practices. For motors which have been applied during the war under Conservation Order L-221 of the War Production Board, the relay tables had to be modified to take into account the elimination of the service factor.

Thermal overload relays are often used with motors rated on a different basis from continuous and 40 C rise. If specific application data on the heating of such motors are not available, which would permit an accurate check of the overload relay selected, the following will serve as a guide for selecting heaters from a standard table for 40 C rise motors as published by the relay manufacturer. This table may not be accurate for all motors, but it works out well in the majority of cases.

Motor Rating Basis	*Continuous Capacity of Motor in Terms of Rating*	*Select Heater for Current Given in Relay Table, Multiplied by*
40 C rise, continuous	115%	1.0
50 55 C rise, continuous	100%	0.9
50 55 C rise, 1 hour	80%	0.8
50 55 C rise, 30 minutes	70%	0.75
50 55 C rise, 15 minutes	55–60%	0.70

Instantaneous Overload Relays

Instantaneous overload relays are electromagnetic devices in which an armature is attracted by the flux produced by the load current flowing in the coil. The relays open their contact when the motor current exceeds a definite set value. The purpose of such relays is to protect both the motor and the driven machinery against damage due to suddenly applied high overloads. The relays offer no protection against burn-out of a motor on sustained light overloads, but they do protect against mechanical and electrical damage to the motor and the machinery if gears bind, a drive jams, or some faulty operation by the attendant throws an excessive load on the motor.

On d-c systems, which generally produce only comparatively low short-circuit currents, and on some a-c applications on power systems with limited short-circuit capacity, instantaneous overload relays have been used for short-circuit protection, and a contactor interrupts the short-circuit current. Such relay application can be considered only if the interrupting capacity of the contactor is adequate for the short-circuit current of the system to which it is connected. If the short-circuit capacity of the system exceeds the interrupting ability of the contactor, other means than overload relays must provide protection, as discussed later in this chapter.

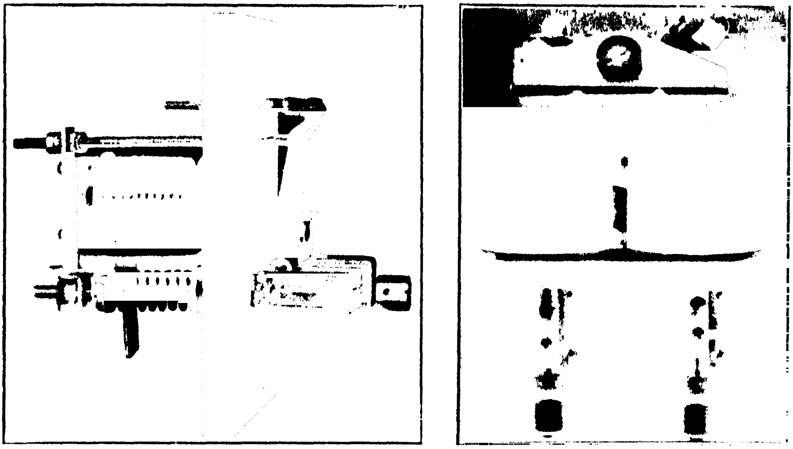


FIG. 267. Instantaneous overload relays. *A*. For use with d-c motors. *B*. For use with d-c or a-c motors.

Shown in Fig. 267 are two commonly used types of instantaneous overload relays. The left-hand relay is a single-pole type, for use on d-c circuits. The magnet core, carrying the current coil, is behind the panel, and the contact is in front of the panel. The magnet structure is solid, precluding the use of this relay on a-c controllers because of eddy current losses. The right-hand relay can be used on both d-c and a-c controllers. It has two coils; thus one relay can protect a polyphase motor or two d-c motors. A plunger is drawn into the coil when the current exceeds the relay setting, and the impact of the plunger opens the contact.

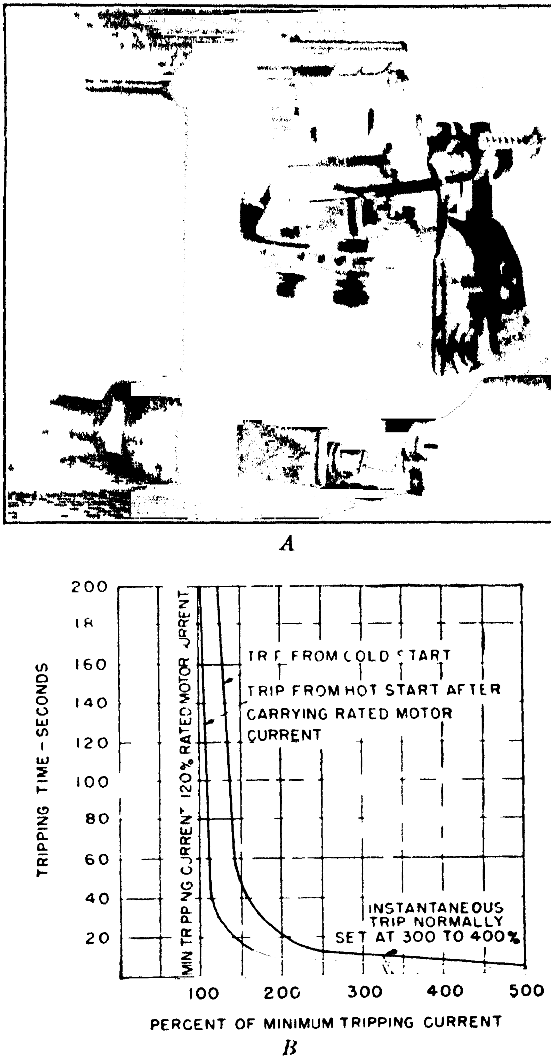
Instantaneous overload relays are used principally on controllers for intermittent-rated drives such as cranes, hoists, and the like. The relays must be set high enough so that they will not trip on starting current. Instantaneous overload relays are usually set to trip between 250 and 300 per cent of motor full-load current. As motors for intermittent-duty applications are generally selected so as to develop sufficient torque for the worst starting condition, there is little danger of motors overheating from sustained overloads, because "on" time of such motors is generally too short for the motor to come up to temperature.

Inverse Time Overload Relays

The most important intermittent-duty d-c drives use mill type motors which possess an inherent high overload capacity. Opinion on the best practice for protecting such motors is divided. Whereas one school of thought considers fast-operating instantaneous relays, which are set high, adequate protection, other operators prefer to use inverse time overload relays. Such relays are similar to instantaneous relays, but the opening of the contact is delayed by some suitable time delay attachment. Inverse time relays trip after a definite time on moderate overloads, whereas they trip fast on high overloads or short circuits. Thus they provide some protection for the motor against sustained overloads, whereas they protect both motor and drive against excessively high current and torque peaks.

One method of obtaining an inverse time tripping characteristic is to add an oil or air dash-pot to an instantaneous overload relay. The dash-pot restrains the plunger movement, and the time delay depends on the magnitude of the coil current. The tripping characteristic can be influenced by suitable release vents. The principal objection against dash-pots is that they must be carefully serviced, since dust and dirt, which may enter the dash-pot, will affect the tripping time. The performance of oil dash-pots is furthermore influenced by the viscosity of the oil which depends on the ambient temperature. If oil is left too long in a dash-pot it is likely to sludge so that dash-pot oil must be renewed at regular intervals.

These disadvantages are overcome by the relay shown in Fig. 268, the time delay of which is obtained by magnetic action. The armature of the relay, which is attracted by a series coil, is restrained by the magnetic flux emerging from a strip of nickel-iron alloy called Invar. This material changes its magnetic property under the influence of heat, and it loses its permeability at approximately 240 C. A heater, connected in parallel with the relay coil, heats the Invar strip as a function of load current. When the Invar strip loses its permeability, the lock-out action ceases, and the relay armature picks up and opens the relay contact. An auxiliary armature, which is attracted to the coil at high currents, moves the Invar strip mechanically and permits the relay armature to pick up instantaneously.


A

B

Fig. 268. Combination instantaneous and inverse time d-c overload relay. A Front view of relay. B Tripping curve. (Courtesy Westinghouse Electric Corp.)

The tripping curve of the relay is plotted in the lower sketch B of Fig. 268. The inverse time characteristic varies with the initial temperature of the Invar strip. For a given current, the tripping time is longer for a start from a cold condition than after the relay had carried current. The instantaneous tripping current can be adjusted independent of the inverse time trip. The relay contact is reset either automatically or by hand, depending on the position of an externally turn-button-operated latch.

Protection against Short Circuits [5, 6, 7]

General-purpose industrial control equipment is usually rated in amperes or horsepower. Thus the rating is indicative of the normal load and regular operating overloads, such as a stalled motor condition, which the control equipment is designed to handle. Control equipments may be subjected to high thermal and mechanical stresses as a result of short circuits occurring on the load side of the control apparatus. A complete control equipment must include protection against damage of the control devices by the destructive forces of a short circuit.

The magnitude of the short-circuit current which may occur at any point in an industrial power system bears no relation to the size of the motor and the rating of the control equipment installed in any branch circuit. The short-circuit current is solely determined by the characteristics of the power system. The symmetrical short-circuit current flowing at the location of the fault is equal to the system voltage divided by the sum total of the impedances between the generator and the fault. During the first half cycle an unsymmetrical current of nearly twice the symmetrical short-circuit peak current may flow. The unsymmetrical short-circuit current peak determines the maximum mechanical stress to which controller parts may be subjected. As protective devices which interrupt the short-circuit current during the first half cycle may prevent the short-circuit current from attaining its full value, the short-circuit current which would flow if no protective devices were in the circuit is called the "available short-circuit current," and it forms the basis on which protective devices are selected for a given installation.

Magnetic controllers are able to interrupt ten times their normal rated current. They are also able to carry fifteen times their rated current for one second. Many power supply systems exist, to which such controllers are connected and which under conditions of short circuit or ground fault are able to supply currents greatly in excess of the values given above. It is considered beyond the scope of this book to present methods to calculate the short-circuit current which may flow in a power system. The reader who is interested in making a short-circuit study should refer to available literature on that subject.[8, 9, 10, 11]

To convey an idea of the magnitude of short-circuit currents which may be encountered on an industrial power system, the following statements should be of interest:

1. The available short-circuit current in a d-c system may range from a few thousand up to considerably over 100,000 amperes. The value of current will depend on the characteristics of the source and the load under short-circuit conditions, together with the location of the fault with respect to the power sources.
2. The available short-circuit current in low-voltage a-c systems, up to 600 volts, may be as high as 100,000 amperes rms. The value of current will depend on the total reactance in the circuit from the point of fault to the source of power.
3. In high-voltage a-c systems of 2300 or 4000 volts, short-circuit values as high as 150,000 to 250,000 kva are frequently encountered. In relatively few installations it may be possible to obtain values as high as 500,000 kva.
4. While the foregoing statements indicate possible maximum values, proper system design, including the consideration of the power source capacity, usually keeps the short-circuit currents down to values materially lower than those indicated above.

The figures given above indicate that industrial control contactors may be subjected to fault currents greatly in excess of their ability to interrupt or to carry for any length of time. Recognizing this condition, the National Electric Code[4] requires branch circuit protection ahead of industrial control equipment, which is intended to protect the branch circuit conductors, the control apparatus, and the motor against damage by fault current. The motor branch circuit protective devices must be able to carry the starting current of the motors, but their rating or setting must not exceed the values given in Tables 18 and 19, unless it is impossible to start the motor with such settings. In such a case, the protective device may be selected on the basis of a higher current rating, which, however, must not exceed 400 per cent of the motor full-load current.

There are two recognized devices which may be used for branch circuit protection, namely, fuses and time limit air circuit breakers. The maximum permissible ratings prescribed by the National Electric Code are given in Table 18 for various types of motors not marked with a code letter. Code letters have been introduced for all

TABLE 18

MAXIMUM RATING OF MOTOR BRANCH CIRCUIT PROTECTIVE DEVICES FOR MOTORS NOT MARKED WITH A CODE LETTER

	Per Cent of Full-Load Current		
		Circuit Breaker Setting	
Type of Motor	*Fuse Rating*	*Instantaneous Type*	*Time Limit Type*
Single-phase, all types	300		250
Squirrel cage and synchronous (full voltage, resistor, or reactor starting)	300		250
Squirrel cage and synchronous (auto-transformer starting)			
Not more than 30 amperes	250		200
More than 30 amperes	200		200
High reactance squirrel cage			
Not more than 30 amperes	250		250
More than 30 amperes	200		200
Wound rotor	150		150
Direct current			
Not more than 50 hp	150	250	150
More than 50 hp	150	175	150

single-phase and polyphase squirrel cage motors and synchronous motors rated ½ hp and larger. The code letter designates the locked rotor starting kva per horsepower as follows:

Code Letter	*Kva per Hp Locked Rotor*	*Code Letter*	*Kva per Hp Locked Rotor*
A	0.0 -3.14	J	7.10- 7.99
B	3.15 3.54	K	8.00 8.99
C	3.55-3.99	L	9.00- 9.99
D	4.00 4.49	M	10.00-11.19
E	4.50 4.99	N	11.20-12.49
F	5.00 5.59	P	12.50 13.99
G	5.60-6.29	R	14.00 and above
H	6.30-7.09		

Table 19 lists the maximum permissible rating of motor branch circuit protective devices, as established by the National Electric Code for motors that are marked with a code letter.

When selecting either a fuse or a circuit breaker for protecting an industrial controller, consideration must be given to the time required for the protective device to operate after the fault has occurred. During that interval of time the controller is subjected to

TABLE 19

MAXIMUM RATING OF MOTOR BRANCH CIRCUIT PROTECTIVE DEVICES FOR MOTORS MARKED WITH A CODE LETTER

	Per Cent of Full-Load Current	
Type of Motor	*Fuse Rating*	*Circuit Breaker Setting, Time Limit Type*
All a-c single-phase and polyphase squirrel cage and synchronous motors (full voltage, resistor, or reactor starting)		
Code letter A	150	150
Code letters B to E	250	200
Code letters F to R	300	250
All a-c squirrel cage and synchronous motors with auto-transformer starting		
Code letter A	150	150
Code letters B to E	200	200
Code letters F to R	250	200

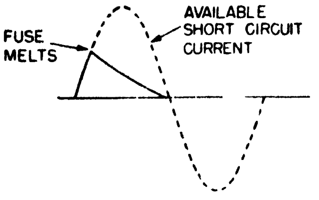
stresses due to the fault current. The less the energy permitted to flow through the controller during the fault, the less the probability of damage due to fault current.

Small contactors, NEMA size 3 and smaller, have limited thermal capacity. To prevent overheating of current-carrying parts, the protective device should interrupt the fault current in less time than one half cycle. Tests have shown that NEC (National Electric Code) non-renewable cartridge fuses, when selected in accordance with Table 18, provide adequate protection. In establishing the fuse rating for a given motor, the following factors have to be considered. If the fuse is too small, it overprotects the motor and blows on overloads which should be taken care of by the overload relay. If the fuse is too large, too long a time is required to interrupt the fault current and overheating of the controller may result during the duration of the fault. These are the reasons that under no circumstances should the fuse rating exceed 400 per cent of motor full-load current.

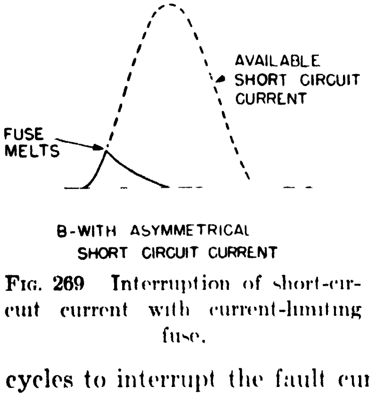
Larger contactors, NEMA size 4 and larger, have greater thermal capacity and are able to withstand the effects of fault currents for several half cycles. Air circuit breakers, such as described in Chapter 6, are used with such contactors. Such breakers have an inverse time tripping characteristic for moderate overcurrents, preventing the breaker from tripping on motor starting inrush current. Under high short-circuits currents, these breakers open instantaneously, and an adequate air circuit breaker interrupts a short-circuit current, equal to its interrupting rating, in four half cycles or less. Instantaneous trip breakers are often used on d-c circuits but not on a-c circuits.

High-Voltage Current-Limiting Fuses[12, 13]

Many installations of industrial control equipment are in use today on 2300- and 4600-volt systems, the only short-circuit protection of which consists of oil circuit breakers in the substation. Such protection used to be considered adequate as long as industrial power systems were small, and the short-circuit currents under the worst condition amounted to only a few thousand amperes. With the growth of power systems in industrial plants, especially when connected to large public utility networks, available short-circuit currents have risen to many thousand amperes. Short-circuit currents of such magnitude are greatly in excess of the interrupting capacity and the short time current-carrying ability of control apparatus. Circuit breakers and high-voltage fuses, which require several half cycles to interrupt the fault current, permit the short-circuit current to flow too long through the controller, and severe damage has occurred to control devices under fault conditions.



A-WITH SYMMETRICAL SHORT CIRCUIT CURRENT



B-WITH ASYMMETRICAL SHORT CIRCUIT CURRENT

FIG. 269 Interruption of short-circuit current with current-limiting fuse.

Current-limiting fuses, which were introduced in the United States in the late 1930's, afford excellent protection to industrial control equipment. A current-limiting fuse is a fast-acting fuse, consisting, for instance, of a silver wire embedded in quartz sand which interrupts the short-circuit current during its initial rise in the first half cycle. Thus the current is interrupted before it has reached the first peak of the available short-circuit current. In Fig. 269 the current-limiting action is illustrated. The dashed curves are the available short-circuit current, drawn both for the symmetrical and the asymmetrical case. The solid curves are the currents actually flowing in the controller. Because of the steeper initial rise of current, the fuse interrupts at a higher current when the short-circuit current is symmetrical. Fuses are rated on the basis of their ability to interrupt the available short-circuit current of the circuit on which they are installed. No code has yet been established governing the application of such fuses to control equipment, and the manufacturer's recommendations should be followed in selecting the proper fuse size for a given controller.

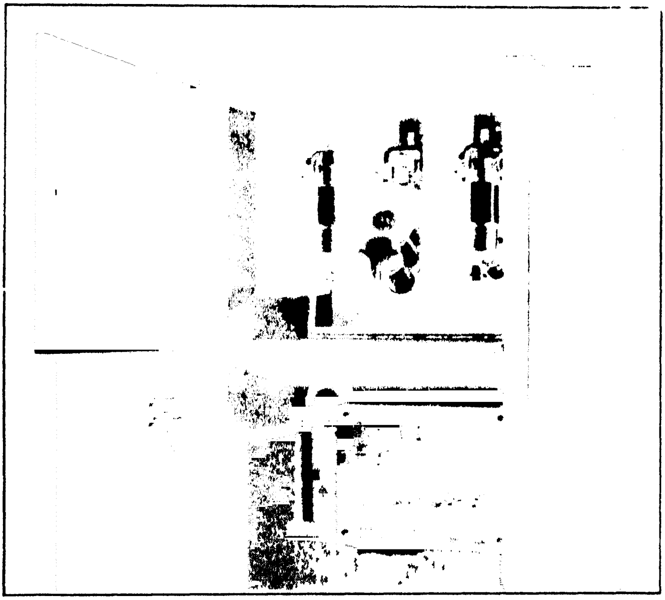


FIG. 270. Current-limiting fuses in top compartment of high-voltage controller.

When applying current-limiting high-voltage fuses, the same factors have to be considered as in the application of low-voltage fuses. The fuse should have a sufficiently high current rating so that it will not interrupt on starting and operating overloads. It should not be too large to interrupt the short-circuit current for which the fuse is selected during the initial current rise in the first half cycle.

In appearance, current-limiting fuses do not differ greatly from conventional fuses. In Fig. 270 a set of three fuses is shown installed in the top compartment of a 2300-volt starter. The fuse fittings are arranged so that the fuses can be used as switch-hook-operated disconnect switches, eliminating the use of separate disconnect switches.

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CHAPTER 15

SOLENOIDS, THRUSTORS, BRAKES

Solenoids and Thrustors are devices which convert electric energy into mechanical energy, associated with linear motion. Their output is measured in pounds pull or thrust at a stroke or gap in inches. The product of their force and stroke has the unit of inch-pounds, which is comparable to the torque developed by a motor and represents the mechanical work that can be done at constant force. Although some of these devices are used directly as a source of power for process machinery, the majority are applied as actuators for some mechanical control devices, such as valves, dampers, and the like. They are also used to trip mechanical latches or to load spring-operated machine parts, and many are used on mechanical brakes. Thus solenoids and Thrustors are usually regarded as control devices, and built by manufacturers of control equipment. Because they are often applied in conjunction with magnetic control, a brief outline of their function and their application data is given in this chapter.

Alternating-Current Solenoids

Shown in Fig. 271 is a typical solenoid for use on a-c circuits. The frame consists of thin silicon steel laminations, which are varnished to reduce eddy current losses. The stack of laminations is riveted together, and heavy outside punchings provide the necessary rigidity. Mounting feet, in the form of angle brackets at the top and bottom, form part of the riveted structure and permit mounting of the solenoid at either end. Similarly, the plunger consists of laminations, riveted together to form a solid body. One end of the plunger (the pole face) and a corresponding section of the frame (the seat) are carefully ground so that the plunger, when fully attracted, is accurately seated against the frame. This accurate seating is important, to prevent the magnet from being noisy. Pole shaders, as described on page 172, are provided to keep solenoids from chattering. An air gap or a spacer of non-magnetic material must be inserted somewhere in the magnetic path so that the plunger will not stick closed because of residual magnetism when the coil is de-energized.

Coils are wound on molded or metal spool bodies. They are held in position by leaf springs between the frame and the spool body. Plunger guides of brass or beryllium copper prevent the plunger from wearing the spool body.

Solenoids are available either as pull type or push type. The solenoid of Fig. 271 has the load attached to the head of the plunger. When energized, the solenoid pulls up the load. A push type solenoid has an extension on the plunger, protruding through the top of the frame. A load attached to the extension is pushed up when the solenoid is energized.

FIG. 271. A-c solenoid.

The physical dimensions of a solenoid determine its rating. The maximum stroke should not exceed one half the plunger length. The pull is equal to the force of attraction between frame and plunger. It is determined by the cross section and reluctance of the magnetic path and the ampere-turns of the coil. When voltage is applied to the coil, the current is equal to terminal voltage divided by coil impedance, which is the vector sum of resistance and reactance. Depending on the position of the plunger in the frame, the air gap changes and with it the reactance of the coil and the reluctance of the magnetic path. The pull of the solenoid varies as the plunger moves along the path of its stroke. The rated pull is the minimum pull within the range of rated stroke.

Plotted in Fig. 272 are pull versus stroke of a certain solenoid with various coils. Curve *A* is for use with a 60-cycle coil, and curve *B* is a corresponding plot with a 25-cycle coil. Curves are given both for rated coil voltage and for 85 per cent of rated coil voltage. Two magnetic forces act on the plunger. One is the attraction between the pole face of the plunger and the seat. The other is the *solenoid force*, which pulls the plunger into the center of the magnetic field, that is, into the center of the coil. The force of attraction rises steadily as the stroke becomes shorter, because of the reduction in air gap between the pole face and the seat. The solenoid force varies along the path of the stroke because the coil current changes as the impedance changes with the position of the plunger. The difference in the change in coil impedance accounts for the difference between pull curves for 60 cycles and 25 cycles. Near the end of the stroke, the pull rises sharply, and the plunger strikes its seat with a blow. The differences between the net pull and the load must be dissipated by the impact. Thus no advantage is gained by using an oversize solenoid because the extra impact force experienced when the plunger seats tends to reduce the life of the solenoid.

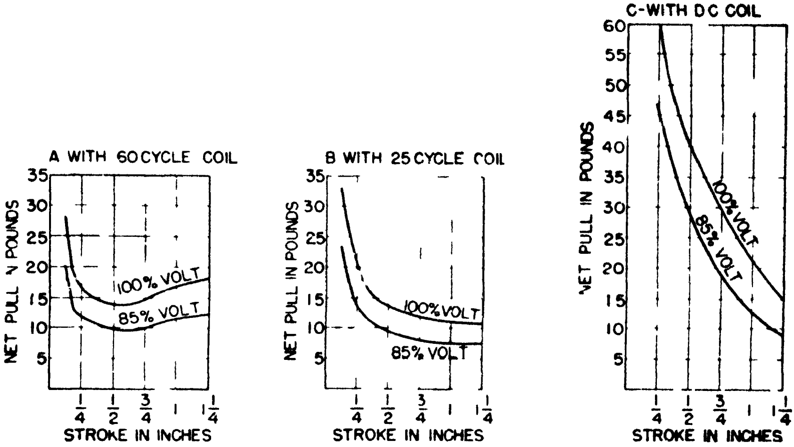

FIG. 272. Pull curves of solenoid with a-c and d-c coils. Tests taken with plunger operating against gravity; plunger weight 1.18 pounds. Data taken with coil at 125 C. Solenoid rating: Maximum stroke 1¼ inches. Pull 9 pounds at 60 cycles at 85 per cent voltage; 7 pounds at 25 cycles at 85 per cent voltage; 9 pounds at direct current at 80 per cent voltage.

With variations in voltage, the solenoid pull varies theoretically as the square of the voltage. Actually, saturation of the iron reduces the pull somewhat at increased voltage, particularly when the gap is small. It is customary to publish the pull of solenoids at rated voltage and at 85 per cent of rated voltage. If the available control voltage source varies considerably, the solenoid must be selected on the basis of 85 per cent of rated voltage, in order to make certain that sufficient pull is developed regardless of voltage conditions. If the supply voltage is constant, best results are obtained by applying the solenoid on the basis of its full voltage rating because impact is then reduced and longer life results.

In designing mechanical linkages between solenoid and load, care must be taken to permit the plunger to seat fully. If mechanical parts prevent the plunger from sealing against the seat, the air gap in the magnetic path is increased, reducing the impedance of the coil and causing the coil current to be higher than its rated value. As a result, the coil will overheat and burn out.

Direct-Current Solenoids

Solenoids operated by direct current do not require a laminated magnetic structure, and solenoids are on the market designed especially for d-c operation, with continuously rated coils. Some manufacturers are adapting their standard line of a-c solenoids to d-c applications in order to obtain a better production set-up, using the same frames and plungers.

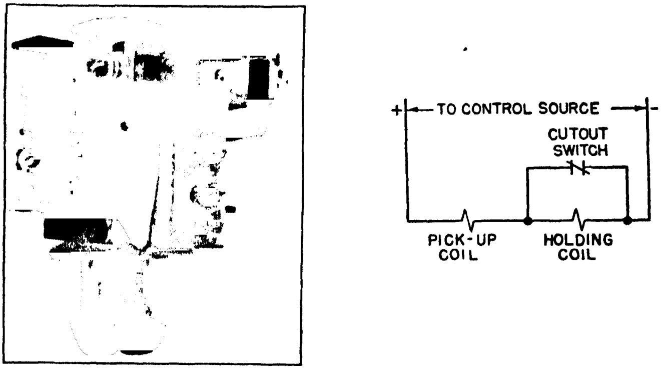

Fig. 273. D-c solenoid with cut-out switch.

As the current through a d-c coil is governed only by its resistance, which does not change with the position of the plunger, the coil current on pick-up must be high enough to pull the plunger against its rated load at maximum air gap. It would be uneconomical to design a coil which would stand pick-up current indefinitely without overheating. Many d-c solenoids are therefore built with two-section coils and a cut-out switch. Such a solenoid and the connections of its coil circuit are shown in Fig. 273. The pick-up coil has low resistance and produces sufficient ampere-turns to lift the plunger and rated load. The holding coil has a high resistance. With the plunger dropped out, the holding coil is short-circuited and only the pick-up coil is effective. When the plunger is almost seated, it actuates a lever which opens the cut-out switch and inserts the holding coil in series with the pick-up coil. The combined resistance of the two coils reduces the coil current to such a value that the coil temperature stays below the permissible rise of 85 C. With this current, the plunger pull is sufficient to keep the plunger from dropping out under its rated mechanical load.

As in the case of a-c solenoids, the pull rises as the plunger travels through its stroke. The rise in pull is even higher than with corresponding a-c solenoids, because the coil current does not drop when the plunger approaches its seat. In Fig. 272, curve *C* is a plot of net pull versus stroke of a solenoid with d-c coil, which is of the same size as the one used for determining curves *A* and *B*. The high pull at reduced air gap increases the impact of the plunger upon seating, and it is even more imperative to avoid the use of oversize solenoids.

Thrustors [1]

A Thrustor is an electrohydraulic mechanism which converts electric energy into a straight-line, constant thrust. In this respect, a Thrustor differs basically from a solenoid in that the force it delivers is constant throughout the stroke. Shown in Fig. 274 is a sectional view of a Thrustor, exposing its internal working parts, as well as an external view of a complete device.

It consists of a cast or seamless tube tank, filled with oil, in the bottom of which is located a centrifugal pump. The impeller is driven by an electric motor which is assembled on the top cover of the tank. Inside is a piston with two push rods, connected to a cross bar, which delivers the useful thrust. When the impeller is driven by the motor, pressure is built up under the piston, which moves upward. With the motor and pump impeller stopped, the load forces the piston down, and the oil is by-passed around the piston.

Thrustors have been built for thrusts up to 3200 pounds and strokes up to 16 inches. They are most widely used on three-phase systems, permitting squirrel cage motors to be used for driving the impeller. It is the simplest and most reliable type of motor available, which enhances the ruggedness of the device. Thrustors can be built with single-phase or d-c motors.

No injury to the motor results from stalling of the Thrustor. If the Thrustor is overloaded at any position in its stroke, the piston stays there and the impeller simply spins in the oil. Removing the overload causes the piston to rise to the top position, and again the impeller keeps on spinning in the oil, thus eliminating the two chief disadvantages of solenoids. There is no sudden rise in force near the end of the stroke. Also no burn-out can occur if the load is greater than the rating of the device.

Variations in line voltage up to 15 per cent undervoltage have no effect on the rated thrust. Overvoltages up to 10 per cent are permissible without injury to the motor. Variations in frequency cause a change in motor speed and affect the thrust approximately as the square of the motor speed.

Thrustors are inherently more sluggish than solenoids, since a certain time is required to pump the necessary quantity of oil. The minimum time of up stroke travel of the cross bar is 0.25 second per inch plus the starting time, which is between 0.3 and 0.5 second, depending on Thrustor size. By means of restrictions in the oil path, the travel time can be increased to any desired value, should the application call for slower than normal travel.

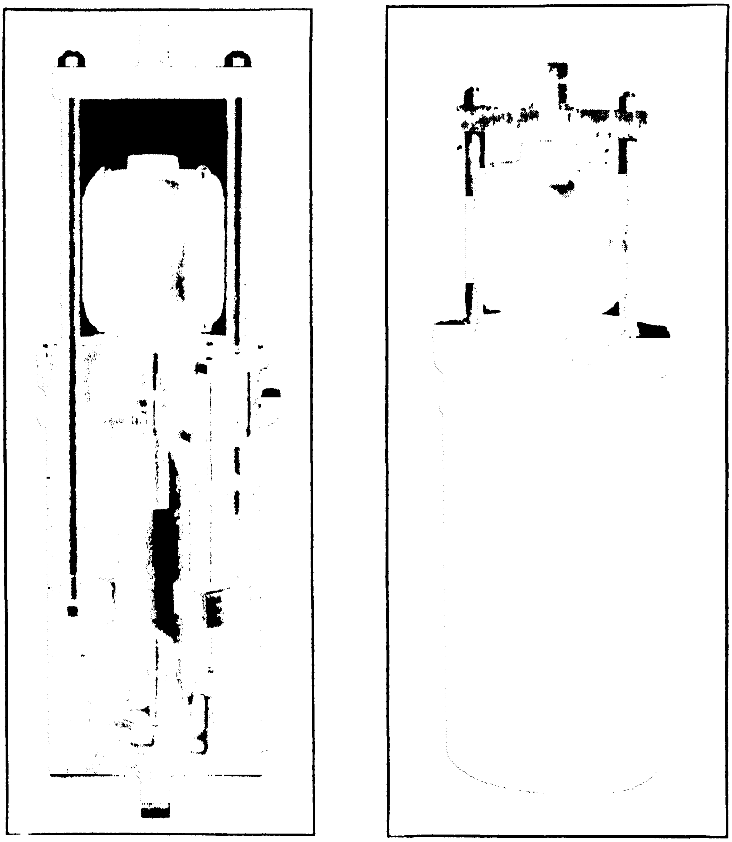

FIG. 274. Sectional and plain view of Thrustor.

Similarly, when the Thrustor is de-energized, a certain travel time is required for the down stroke. The minimum time depends upon Thrustor size and load and is of the order of 0.5 second. If a baffle is used in the return path of the oil, which can be adjusted from the outside, it is possible to increase the down stroke time to 10 seconds.

Thrustors can be supplied with a suitable base for rigid mounting or for clevis mounting. A Thrustor without base is shown in the right-hand view of Fig. 274, and a Thrustor with base for clevis mounting is shown in the left-hand view of Fig. 274. Thrustors may be tilted up to 45 degrees either side of vertical, without lessening of stroke or thrust, or loss of oil.

Types of Brakes [2, 4]

Many motor applications require a mechanical brake. Ability to stop quickly and accurately may be of importance. Mechanical brakes, either alone or in conjunction with some form of electric braking, are used for that purpose. Or a load may have to be held against the effect of an extraneous force, such as gravity. Hoists are a typical example of a drive requiring a brake to hold a load after it has been stopped.

A brake consists essentially of a wheel or disk, against which a band or shoe of suitable friction material is pressed. Weights or springs can be used to supply the necessary pressure. Weights have the disadvantage that their mass stores energy, possibly causing pressure peaks to occur when the brake is applied. Springs, which store practically no kinetic energy, are used nearly exclusively to supply brake pressure. Electrically operated brakes are generally spring-set, electrically released Occasionally, inverted brakes are used, for instance to hold the weights of rail clamps on crane bridges, where springs release the brake and electrical operators apply the brake.

Two kinds of problems are involved in the design and application of brakes. One set of problems is purely mechanical and concerns the torque which a brake develops to hold a load, or the energy a brake is able to dissipate when stopping a load. The other problems concern the electrical operating means which are governed by the power supply, circuit design, and desired speed of response.

Considering first the mechanical part of the brake, there are three commonly used types, namely, disk, band, and shoe brakes. Disk brakes are built only in the smaller sizes and for applications where duty is not severe. They are compact and particularly suited for motor mounting. Shown in Fig. 275 is an a-c disk brake, mounted on a squirrel cage induction motor. The brake cover is partially cut away to expose the internal parts. A system of metal disks, mounted on the motor shaft, rotates with the motor. A system of plates of friction material can move axially. With the brake deenergized, the friction plates are pressed against the metal disks by a spring. With the brake energized, a pair of magnets unloads the friction plates and they run then clear of the metal disks. The whole brake is enclosed in a bell-shaped housing, assembled to the motor end shield. Motor and brake are assembled at the factory, and no provisions for mounting and lining up the brake have to be made at the installation.

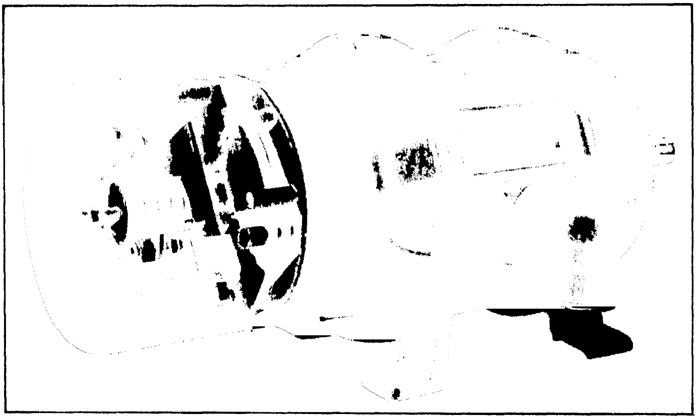

Fig. 275. Disk brake.

Band brakes have the friction material mounted on a continuous steel band which lies around a brake wheel mounted on the motor shaft. They are one of the earlier types of brakes. Their principal advantage is that they cover a wide arc of the wheel, as much as 90 per cent of the total wheel surface, thus reducing the pressure per unit area. The action of the band is that it tends to tighten itself in one direction of rotation. The band keeps dust and water off the wheel, which results in nearly constant coefficient of friction. The important disadvantages are the difficulty of raising the band entirely off the wheel and of obtaining equal braking torque in both directions of rotation. These difficulties can be overcome by subdividing the band into several pieces, shaped like shoes, and supporting the pieces correctly. Figure 276 is a view of a three-piece band or three-shoe brake.

Shoe type brakes have the friction material fastened to two shoes which are applied to the wheel from opposite sides. Each shoe covers an arc of approximately 90 degrees, experience having shown that not much braking effect is gained by choosing a greater arc. Thus approximately 180 degrees of the circumference of the wheel

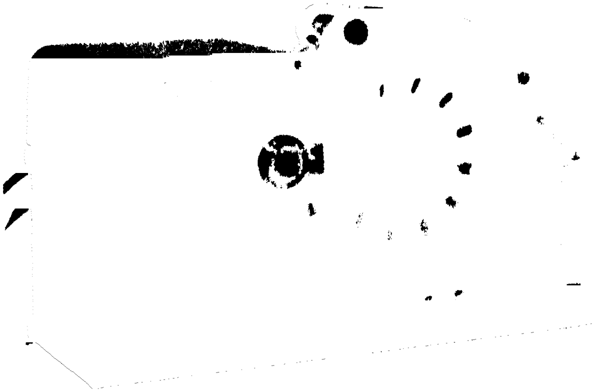

FIG. 276 Three-piece band or three-shoe brake.

are utilized for braking. A typical two-shoe brake with wheel is shown in Fig. 277. The shoes are individually adjustable and self-

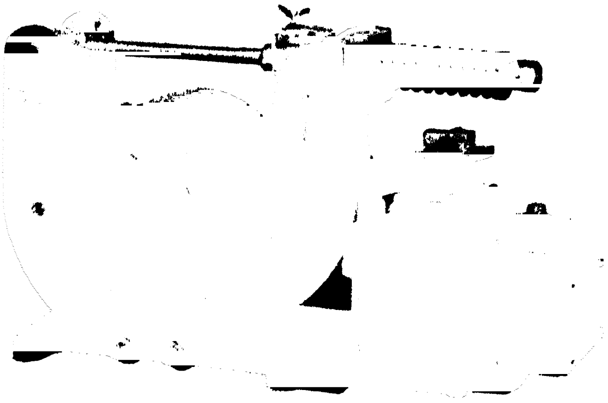

FIG. 277. Solenoid-operated two-shoe brake.

aligning; only a short stroke of the operator is required to release the shoes clear of the wheel, and all parts are simple and easily accessible.

The following table gives a comparison of the three types of brakes with respect to their operating characteristics:

	Disk Brake	*Band Brake*	*Shoe Brake*
Service to which adapted	light	heavy	heavy
Motor mounting	easy	in small sizes	in small sizes
Braking torque	limited	high	high
Heat dissipation	fair	fair	good
Adjustment	easy	difficult	easy

Brake Operators

Electrical operators to release brakes are clapper magnets, solenoids, torque motors, and Thrustors. Clapper magnets have a short stroke and low inertia. The disk brake of Fig. 275 uses two a-c clapper magnets. The three-shoe brake of Fig. 276 has a clapper magnet inside the housing to the left. Clapper magnets have the advantage that the travel of the moving parts is small, which results in fast releasing and setting of the brake.

Solenoids are used principally on d-c brakes, of which Fig. 277 is an example. On a-c brakes, solenoids are used only in the smaller sizes. The impact upon closing of the solenoid places a high strain on the moving parts, especially if the pressure of the brake spring is adjusted below normal. Coils are designed so that they do not overheat on 10 per cent overvoltage. They develop sufficient pull to release the brake at 85 per cent of rated voltage.

D-c brakes are either shunt or series wound. Shunt brakes are equipped with a coil connected across the control bus, and the brakes release when the coil is energized. Shunt brake coils are designed so that they release the brake at 80 per cent of rated voltage and do not overheat at 110 per cent of rated voltage. Series brakes are equipped with a coil through which motor power current flows. Series brake coils are rated in amperes, and they are designed so that the brake will release when 40 per cent of rated current flows through the coil. Once the brake is released, it will stay released on currents down to 10 per cent or less. The use of series brakes has several advantages. The brake cannot release unless current flows through the motor and torque is available at the motor shaft. For this reason, series brakes are most often applied to crane hoists, as it is impossible to release the brake and drop a load should the motor power circuit be interrupted for any reason. Series coils have lower inductance than shunt coils, and they are quicker to release and set. Series coils are wound of heavier wire than shunt coils, which reduces the danger of coil failure.

Large a-c brakes are preferably equipped with a torque motor or a Thrustor. These operators overcome the objections to the use of a solenoid, because both subject the moving parts to a definite force, regardless of stroke, brake wear, or adjustment. Also the operators are quiet, which makes them desirable for use in office buildings or hospitals, for instance on elevators. Figure 278 is a view of a Thrustor-operated shoe brake. The brake wheel is omitted, exposing the lining of friction material.

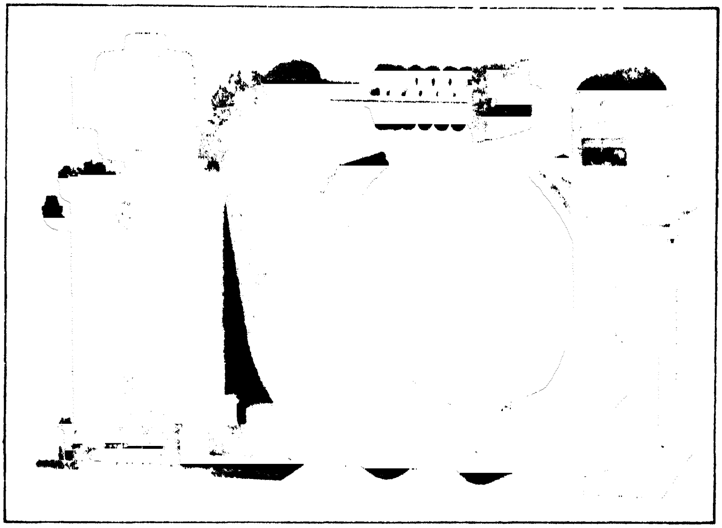

FIG. 278. Thrustor-operated two-shoe brake.

Brake operators are designed to supply the necessary force to overcome the pressure of the brake springs. During normal operation their temperature rise must not exceed the limits established by NEMA standards. Brakes are rated for continuous operation or for short-time operation, either one hour or one half hour. A continuous-rated operator with rated voltage or current applied, does not exceed the permissible temperature rise when the brake is released for an indefinite period of time. If rated voltage or current is applied to a short-time rated operator, the permissible temperature rise is reached after the time on which the rating is based has elapsed. For intermittent-duty applications, brakes are generally selected for the same short-time rating as the motors with which they are used.

In applying Thrustor brakes, it must be considered that they are more sluggish than solenoid-operated brakes. The time for Thrustor brakes to release varies between 0.25 and 0.35 second, depending on brake size and spring setting. The minimum time for Thrustor brakes to set varies between 0.28 and 0.5 second. In many cases this slow setting is an advantage, as it permits appyling the brake smoothly when a heavy mass is to be stopped. Thrustors are equipped with an adjustment so that the brake-setting time can be increased up to a maximum of 10 seconds. Thrustor-operated brakes are particularly suited to stop heavy machinery, such as movable bridges.

Torque Rating of Brakes

Torque ratings of brakes, which are listed in manufacturers' handbooks, are based on the assumption that the brakes are applied as holding brakes and that they deliver a given torque at standstill. Applying brakes for retardation and stopping of loads involves consideration of the character of the load, which is discussed later in this chapter.

The torque which a brake is able to deliver and against which the brake is able to hold depends on the area of the brake wheel, the specific pressure of the friction material against the wheel, and the coefficient of friction. Woven asbestos with an organic binder is the most commonly used type of lining. It is riveted to the brake shoes, with the advantage that it can be renewed at the point of installation, which is not possible with molded linings. The coefficient of friction varies considerably, depending on the condition of the wheel surface and the lining itself. Thus brakes should be protected so that oil and water, which reduce friction, cannot be deposited on the wheel. For calculating torque, the coefficient of friction can be assumed as 0.35. For a two-shoe brake, on which the shoes span 180 degrees of the wheel, the braking torque is

$$T = \frac{0.35\pi D^2FP}{24} \qquad (70) \bullet$$

$$= 0.042D^2FP$$

where T = torque in pounds at one foot radius,
P = average specific pressure in pounds per square inch,
D = wheel diameter in inches,
F = wheel face in inches.

In designing a brake for a given torque rating, a compromise must be made. In order to obtain long life of the lining, P should be low. On the other hand, D should be kept small in order to reduce the inertia of the wheel and the stored energy to be dissipated during retardation.

On most applications the brake is selected so that its torque is equal to rated full load torque of the motor, which is

$$T = \frac{5250\ \text{hp}}{S} \tag{71}$$

where hp = rated full-load horsepower,
S = full-load motor speed in revolutions per minute.

On travel motions of cranes, where motor size is determined by rate of acceleration and where the brake is used as a parking brake only, a brake having a torque rating of less than full-load motor torque is entirely adequate. On the other hand, on hoist applications without electric braking, a brake with a torque rating higher than full-load motor torque must be used in order to stop a load which is accelerated by gravity. Thus considerations of specific applications govern the selection of brakes, which, however, have nothing to do with the basis on which they are rated.

Standard sizes of brakes are listed in NEMA Industrial Control Standards. Ratings of brakes are established in terms of torque only, which means that only brake sizes are standardized, and NEMA is silent on the manner in which the brakes are applied. Table 20 gives a listing of standard d-c solenoid or magnet brakes, and in Table 21, standard a-c brakes are listed. For each size of brake, continuous- and short-time-duty torque rating is obtained by

TABLE 20

STANDARD NEMA RATINGS OF D-C BRAKES

Brake Torque in Pounds at One-Foot Radius			
Shunt Brakes		*Series Brakes*	
Continuous	*One Hour*	*One Hour*	*Thirty Minutes*
3			
10	15		
25	35		
50	75		
70	90	60	90
150	200	135	200
400	525	350	525
675	900	600	900
1350	1800	1200	1800
2700	3600	2400	3600

TABLE 21

STANDARD NEMA RATINGS OF A-C BRAKES

Maximum Torque Rating in Pound-Feet

8-Hour	*Intermittent*
3	
10	15
25	35
50	75
125	160
325	400
600	800
1200	1600
2400	3200

changing the spring tension. The operators are of the same size for either rating, but their electrical lay-out is such that a greater pull is developed for the higher torque ratings. The short-time rated coils, however, cannot be left energized beyond the time indicated by their rating.

Stopping of Load [4]

When a moving mass is brought to a stop by a brake, the kinetic energy of the mass is absorbed by friction. Some friction is always present in any drive, but, unless such friction is high, it is usually neglected in calculating brake performance. It is assumed that all kinetic energy is absorbed as friction between the brake wheel and the brake lining. In order to stop a drive accurately, it is necessary to know the time within which a motor can be stopped.

Assuming that no electric braking is used and that the motor is stopped simply by disconnecting the motor and brake terminals from the line, the following formula can be used to calculate the stopping time:

$$t = t_a + t_d$$

$$t = t_a + \frac{Wk^2S}{308T} \tag{72}$$

where t = total time in seconds, required to stop, after brake has been de-energized,

t_a = time, in seconds, required for brake shoes to apply against the wheel after brake has been de-energized,

t_d = time, in seconds, during which motor drifts to a stop after brake shoes have been applied,

Wk^2 = total moment of inertia of drive in pound-feet^2 (W = weight in pounds of rotating mass, k = radius of gyration in feet) reduced to speed of brake wheel,
S = speed, in rpm, of brake wheel,
T = net retarding torque, in pound-feet, of brake.

Time of brake application t_a varies with size and type of brake. For a specific application, these data have to be obtained from the brake manufacturer. For a-c brakes t_a may be as low as 0.10 second or less on small solenoid brakes. On Thrustor brakes with minimum time adjustment, it may rise to 0.28 to 0.50 second. On Thrustor brakes and on d-c brakes with extra long time adjustment, t_a may be several seconds.

Moment of inertia Wk^2 consists essentially of the motor and brake wheel Wk^2, to which is added the Wk^2 of any other rotating masses, reduced to speed S. If part of the drive, rotating at a speed of S_1 rpm, has an inertia of $W_1k_1^2$, the equivalent inertia at speed S is

$$Wk^2 = W_1k_1^2\left(\frac{S_1}{S}\right)^2 \tag{73}$$

If the load includes parts having linear motion, their equivalent moment of inertia can be determined as follows:

$$Wk^2 = W\left(\frac{V}{2\pi S}\right)^2 \tag{74}$$

where W = weight, in pounds, of moving mass,
V = linear velocity in feet per minute of moving mass.

Retarding torque T is the net torque which absorbs the kinetic energy. If no external forces, such as gravity, are acting on the load, T is the actual torque of the brake, plus friction torque, which is usually neglected. If an external force, for instance gravity, acts on the load, retarding torque T is the brake torque minus the overhauling torque of the load. If the brake torque is equal to the overhauling torque, the load is not brought to rest, for which reason brakes with a torque rating larger than full-load motor torque are often used on hoists. If mechanical brakes are used in conjunction with electric braking, or if slow-setting brakes are applied, a point-by-point calculation must be made, considering the variation of retarding torque as a function of time and motor speed, to determine the stopping time.

Duty Cycle Application of Brakes

Service brakes on intermittent drives are subjected to a duty cycle of being alternately released and set when the motor is started and stopped. During stopping of the motor, kinetic energy, which is dissipated as friction between brake wheel and lining, is transformed into heat. This heat in turn has to be dissipated by the brake. As the lining consists of insulating material, little of the heat generated by friction enters the brake shoe. Practically all heat enters the wheel and has to be dissipated by it.

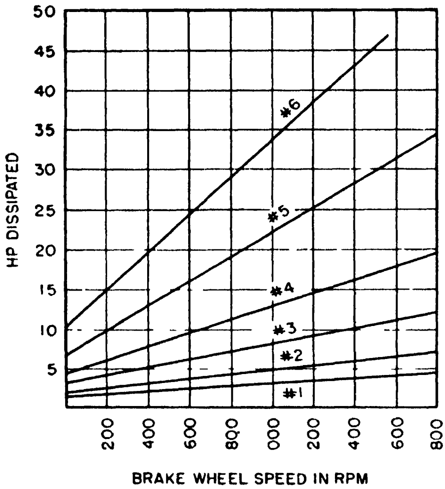

Fig. 279. Heat-dissipating ability of a line of brakes

Although the lining can be neglected as far as heat dissipation is concerned, it limits the maximum permissible temperature. Asbestos contains water of crystallization which begins to distill out of the lining at approximately 500 F. Organic binders oxidize at 450 to 500 F. No standards have been established concerning the permissible temperature rise of brake wheels. It is considered good practice, however, to limit the temperature rise to 400 F.

Heat dissipation of the brake wheel is a function of ventilation, in other words, of the speed at which the wheel turns. As brakes are selected on the basis of motor horsepower, it is convenient to express the heat-dissipating ability in terms of horsepower which can be absorbed without overheating the brake. Figure 279 is a graph, indicating the horsepower that can be dissipated as a function of speed, for a line of six similar brakes of different size. Such a graph is based on heat runs, and, for a specific brake application, the information has to be obtained from the brake manufacturer.

For most applications, brakes are selected on the basis of required torque, and heating does not enter into this selection. If a duty cycle is involved, check the heat-dissipating ability of the brake as follows. The energy stored in the brake wheel during each stop can be calculated by the following formula:

$$E = \frac{WK^2\left(\frac{S}{60}\right)^2}{900} \qquad (75) \bullet$$

where E = stored energy in horsepower seconds,
WK^2 = total inertia of the system in pound-feet^2,
S = speed of brake wheel at instant of brake setting in rpm.

The sum of energy E for all stops during the duty cycle, divided by the duration of the cycle in seconds, is the average horsepower the wheel has to dissipate.

Next, determine the dissipating ability in horsepower seconds for each part of the duty cycle, including standstill periods, from a curve such as Fig. 279. For accelerating and deceleration periods, assume an average speed of one half top speed. Divide the total horsepower seconds thus obtained by the duration of the cycle. This value is the average dissipating ability in horsepower. If this value is larger than the average stored horsepower as determined in accordance with the preceding paragraph, the brake is adequate for the duty cycle. If not, a larger brake has to be used.

Brake Connections [5]

The manner in which brakes are connected in a control circuit has an important bearing on their performance. There are no questions concerning d-c series brakes. They are connected in series with the motor power circuit, and there is no further choice. D-c shunt brakes, however, can be connected in various manners. Shown in Fig. 280 are a number of methods in which such brakes can be controlled.

Sketch *A* shows the power circuit of a d-c shunt motor. The controller is of the simplest kind, a single-pole line contactor interrupting the positive line to the motor, the negative line being solid. The brake coil is connected to the load side of the line contactor. With the motor disconnected from the line, the brake is set, and when the motor is energized by the closing of contactor *M*, the brake releases. When contactor *M* drops out again, to stop the motor, the brake does not set immediately, as the counter emf of the motor armature maintains current through the brake coil. The motor decelerates by the effect of friction, and the brake acts only as a holding brake. This connection should not be used on hoists, as an overhauling load would prevent the brake from setting.

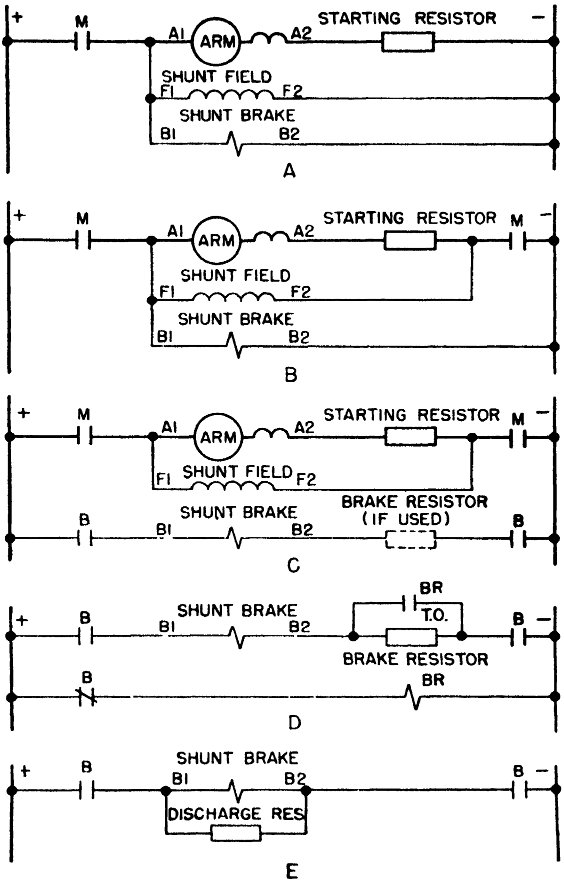

FIG. 280. D-c shunt brake control circuits. *M*. Line contactor. *B*. Brake contactor. *BR*. Brake relay.

Breaking up the current path from the motor armature through the brake coil by a second pole of contactor *M* permits the brake to set immediately when the motor is de-energized. Such a circuit is shown in sketch *B*. Both connections *A* and *B* have the advantage that no additional devices are required for the control of the brake coil. A more flexible arrangement is obtained by introducing a separate brake contactor *B*, as in sketch *C*. The coil of contactor *B* may be energized by an interlock on *M* or by a separate circuit on the master switch or by a separate pilot device. This connection makes it possible to keep the brake released while the motor is de-energized, permitting the motor to drift. Sometimes shunt brakes are used as parking brakes, being set only when the equipment is shut down.

Since the coil of a shunt brake contains resistance and inductance, the speed of brake release, which depends upon the rate of rise of magnetizing current through the brake coil, is governed by the ratio of coil inductance to coil resistance. Using a partial voltage coil with a resistor in series reduces the ratio of inductance to resistance. The rate of coil current rise increases, and the time required for the brake to release is shortened.

Speed of brake release is further increased by the connection of sketch *D*. Relay *BR*, which is of the magnetic time delay drop-out type, short circuits the resistor in series with the brake coil, as long as the brake is set. When contactor *B* closes, the partial voltage brake coil is connected to full line voltage, and the brake releases fast. A normally closed interlock on *B* de-energizes the coil of *BR*, which drops out with a time delay and inserts the brake resistor, preventing the brake coil from overheating.

The speed with which the brake sets is not influenced by the choice of connections *B*, *C*, or *D*. When the brake coil circuit is interrupted, current through the coil ceases to flow immediately. Blowouts on contactor *B* should be used to reduce arcing on the contacts. The brake coil design must allow for sufficient insulation to stand the transient rise of voltage across the terminals of the highly inductive coil. Some applications, for instance the travel motion of heavy bridge cranes, require that electric braking be used for deceleration, and the setting of the brake is delayed for smooth stopping. This delay can be obtained by connecting a discharge resistor in parallel with the brake coil, as shown in sketch *E*. When contactor *B* drops out to set the brake, current through the brake coil does not drop to zero instantly, but it decays gradually, resulting in a corresponding gradual decay in flux, so that the brake sets with a time delay.

Connections of a-c solenoid brakes are shown in Fig. 281. The simplest method is that of sketch *A*. The brake coil is connected across the motor terminals on the load side of the line contactor. No additional contacts for the brake are required, and this connection is widely used with low-voltage motors. Whenever the motor is energized, the brake releases, and whenever the motor is de-energized, the brake sets. Thus the brake acts both as a stopping and a holding brake.

When line contactor *M* opens, voltage across the motor stator terminals does not disappear instantly, but it remains established for a fraction of a second and decays within a finite period of time. Thus, when *M* opens, current through the brake coil is not interrupted immediately, which delays the application of the brake shoes slightly. On drives where *M* is controlled by a limit switch and high accuracy of stopping is required, application of the brake can be speeded up by the circuit of sketch *B*. When *M* opens, the brake coil is disconnected from the stator terminals. The objectionable feature of this connection is that one side of the brake coil remains connected to the line when *M* opens.

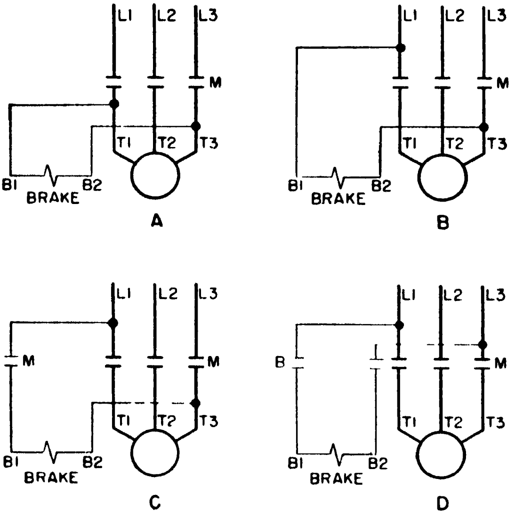

FIG. 281. A-c solenoid brake control circuits. *M*. Line contactor. *B*. Brake contactor.

This objection can be overcome by using an additional contact on line contactor *M*, which is connected in the brake coil circuit (see sketch *C*). The brake coil is de-energized at the same instant as the motor, obtaining somewhat faster setting of the brake.

The most flexible brake control circuit is obtained by the use of separate brake contactor *B*, as indicated in sketch *D*. This connection permits keeping the brake released while the motor is de-energized and drifts retarded only by friction. A separate brake contactor must always be used in connection with high-voltage motors.

Thrustor-operated brakes are connected either directly to the motor terminals or to the power supply through a separate brake contactor.

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CHAPTER 16

MANUAL CONTROLLERS

Although the subject of this book is magnetic control, it is deemed opportune to include a brief chapter dealing with manually operated controllers, as they are used at times in conjunction with magnetic controllers. For instance, on infrequently started wound rotor induction motors, the stator connections are often controlled by contactors because of the ease with which overload protection and safety interlocking can be provided, while the secondary resistors are controlled manually by means of face plate rheostats or drum switches. On an adjustable-voltage controller, the starter for the motor generator set may be hand-operated, because the set is started only once or twice a day. The choice of a manual controller is usually indicated by considerations of cost in such cases where neither safety nor convenience of operation make the use of a magnetic controller imperative.

Face Plate Controllers

Face plate controllers are the oldest and simplest starters for d-c motors. They consist essentially of a box in which the tapped starting resistor is mounted. In front of the resistor is a base with contact buttons, to which the resistor taps are connected. By moving a contact arm, carrying a sliding contact, over the buttons, a connection is established between the line and the motor first through the resistor, and then the resistor is cut out step by step. Figure 282 shows a typical face plate starter for small 115- and 230-volt motors. The operating handle is part of the front cover and engages the contact arm. Undervoltage protection is provided by an undervoltage magnet. The contact arm is restrained by a spring. When the handle is in the running position, the magnet holds the handle there. Upon loss of voltage, the magnet releases the handle, which is then returned by spring action to the starting position, preventing the motor from being connected across the line. upon reappearance of line voltage. The spring also prevents the operator from leaving the handle in an intermediate position, which would cause overloading and burning out of the starting resistor.

The principal weakness of a face plate starter is its limited mechanical life because of the sliding action of its contacts. Also the amount

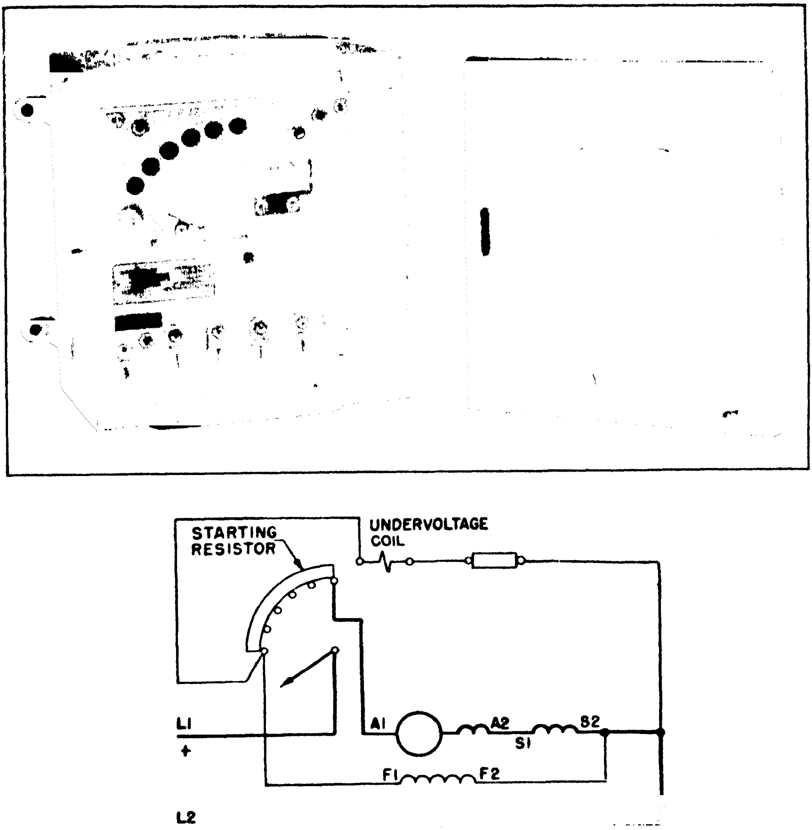


Fig. 282. Face plate starter for small d-c motors

of current which can be broken on the line contact is limited, as the speed of contact opening is slow and a magnetic blowout cannot be arranged conveniently. Starters for larger motors include a magnetic contactor which closes and opens the line connection to the motor, whereas the sliding contacts are used only to short-circuit sections of the starting resistor.

For adjustable-speed motors, combination starters and speed-regulating rheostats are built of the same basic construction. Two rows of contact buttons are provided, one for the control of the armature starting resistor and a second row to control sections of a field-weakening resistor. Part of the control arm travel is used for starting to basic speed, and the remainder for speed control.

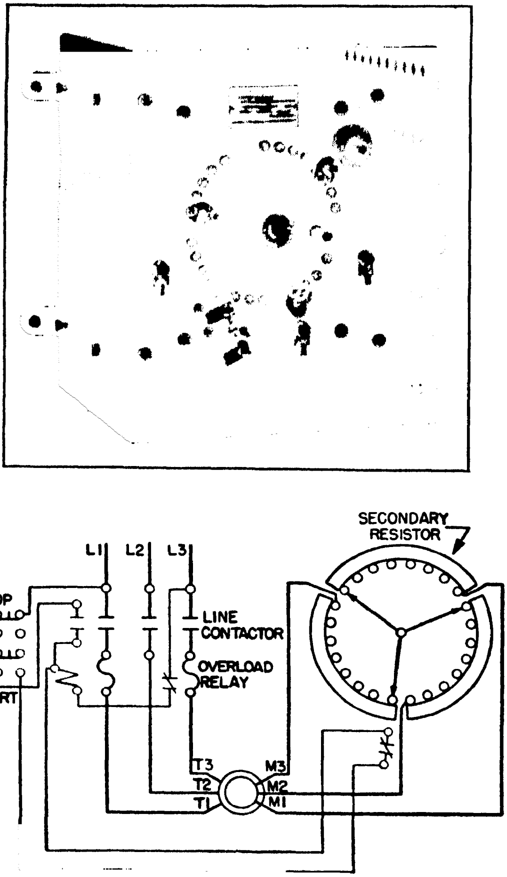


FIG. 283. Face plate secondary controller for wound rotor induction motors.

A face plate type controller for the secondary of a wound rotor induction motor is illustrated in Fig. 283. The resistor consists of three legs, one for each secondary phase. The spider-like contact arm, also consisting of three legs, forms the wye point. Turning the contact arm moves the wye point along the resistor sections and varies the amount of resistance in each secondary phase. Depending on whether the secondary resistor is designed for short-time or continuous duty, the controller can be used for starting or for speed control.

As the face plate controller takes care of the rotor connections only, a separate controller is used for the motor stator connections. In Fig. 283 a magnetic line contactor is shown, with overload relay and start-stop push button station. When the motor is started, the secondary rheostat must be in the starting position where all resistance is connected in each rotor phase. An auxiliary contact is closed in the starting position by the contact arm. This auxiliary contact is connected in series with the start push button, so that the line contactor can be closed only when the secondary rheostat is in the starting position.

Drum and Cam Switches

Although the principal inducement for the use of face plate controllers is their mechanical simplicity and resultant low cost, they lack sturdiness, and their life is unsatisfactory when controllers are operated frequently. Some of the disadvantages of face plate controllers are overcome by drum switches. The linear sliding motion between contact buttons and contact arm is superseded by a rotary sliding motion between stationary contact fingers and circular contact segments, arranged on a drum.

Shown in Fig. 284 is a drum switch for adjustable-speed d-c shunt motors, primarily for machine tool applications. The heavy contacts and segments reverse the armature connections and short-circuit the starting resistor in series with the motor armature. The contacts are separated from each other by arc chutes which can be swung out for servicing of the contacts. A blowout coil, through which line current flows, sets up a magnetic flux which assists in interrupting the arcs formed on the armature circuit contacts. The smaller contacts above the armature contacts insert resistance in series with the motor shunt field, to adjust the motor speed.

The drum switch connections as shown are indicative of the kind of application. A multitude of connections can be obtained by using different arrangements of stationary contacts and drum cylinders. Numerous types of drum switches are on the market, both for d-c and a-c motors, for starting as well as for speed regulation. Especially in the larger sizes, drum switches are available which are suitable for use with magnetic controllers. Motor power connections are then handled by magnetic contactors, and speed control is obtained by the drum switch. Semi-magnetic controllers are often used for a-c motors on drives with sufficiently low frequency of operation, which do not

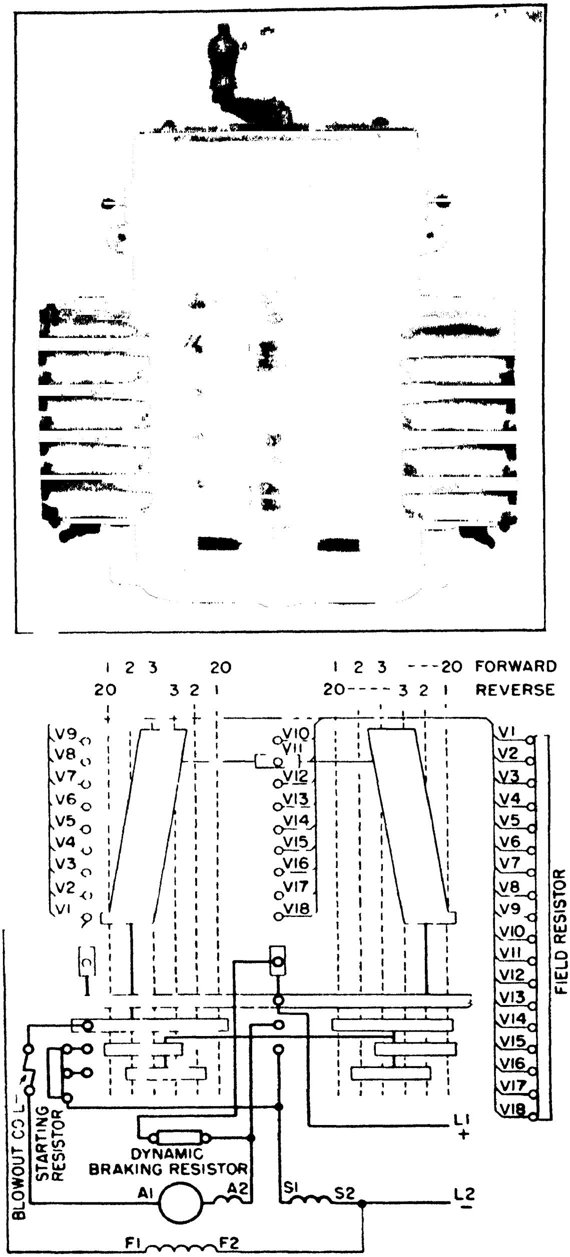


FIG. 284. Drum switch for adjustable-speed d-c shunt motors.

justify the cost of a full magnetic controller. Magnetic line contactors offer the advantage of obtaining overload protection, interlocking with other drives, or limit switch protection. Typical applications on which semi-magnetic controllers are often used are infrequently operated shop cranes, small mine or construction hoists, and small movable bridges.

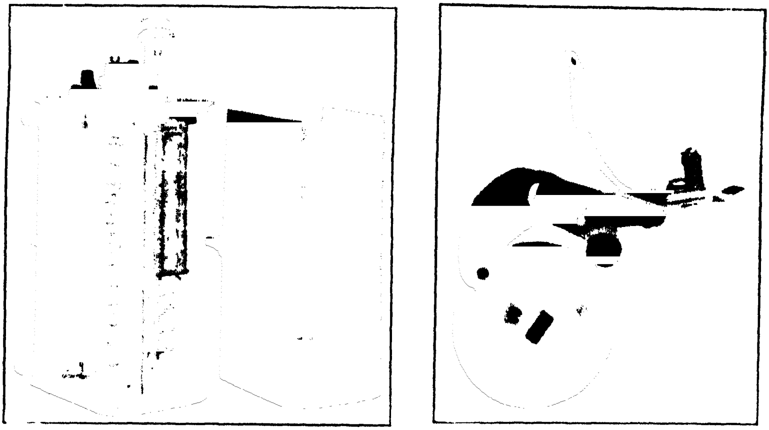


FIG. 285. Cam-operated switch. *A*. General view. *B*. Individual contact unit with actuating cam.

The following advantages of drum switches over face plate controllers are self-evident:

1. The handle is easier to manipulate.
2. Greater flexibility exists in the design of drum developments.
3. Design is more compact and results in sturdier mechanical construction.
4. Contact springs back of the contact fingers maintain higher and more uniform contact pressure.
5. Starting switches can be built either for reversing or non-reversing duty.
6. Blowouts and arc chutes obtain better arc interruption on line contacts.

In spite of these advantages, drum switches have two basic disadvantages. The sliding motion between the stationary contact fingers and the drum cylinder causes high contact wear and prevents quick circuit opening. A number of circuits are tied together electrically in the drum, and the number of electrically isolated circuits is limited

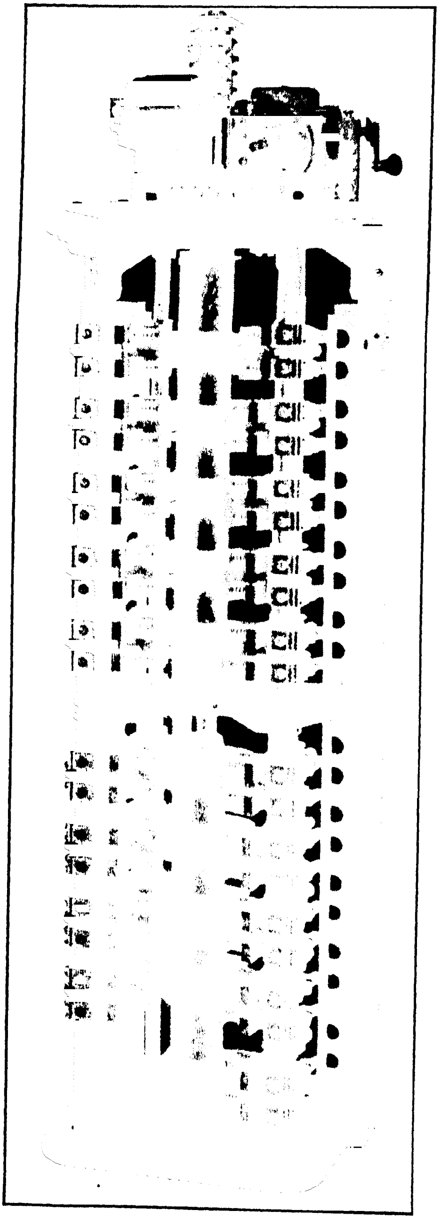


Fig. 286. Motor-operated cam switch for speed control of wound rotor motors rated 600 amperes, 1000 volts, with 20 balanced positions.

for reasons of mechanical design, placing certain limitations on the design of drum developments. A detailed study of a given control application may show that it is either impossible or at least uneconomical to make up a drum development to obtain the most desirable contact closing sequence.

These disadvantages are overcome by cam switches (see Fig. 285). A cam switch resembles a drum switch in overall appearance. However, each circuit is made up of an electrically isolated pair of stationary and movable contacts. Each movable contact is actuated by a set of molded cams which force the contact open and closed. The closing sequence of any contact, with respect to the cam switch position, is determined by the shape of the operating cams. This design realizes the following advantages. Sliding contacts are eliminated in favor of butt contacts, which include a slight sliding motion for self-cleaning, similar to that used in magnetic contactors. As each circuit is completely isolated from any other circuit, there are no restrictions on the cam development or contact closing sequence, which can be made to fit any desired control circuit.

Cam switches are built with contact ratings up to 600 amperes, primarily for the secondary control of wound rotor induction motors. The forces necessary to move such large switches are considerable, and pilot motor-operating mechanisms, as shown in Fig. 286, are sometimes used. The pilot mechanism is designed so that the switch can travel only between definite positions, and contacts cannot be partly closed by stopping the switch between positions. Since only small pilot devices are required to control the pilot motor, such motor-operated switches lend themselves readily to use in conjunction with magnetic controllers.

Motor-Starting Switches

Manual motor-starting switches are used for full-voltage starting of squirrel cage induction motors. They are built similar to a contactor, except that an operating handle takes the place of the operating coil. Two thermal overload relays, one in each of two phases, provide overload protection by tripping a mechanical latch which causes the switch to open. It should be clearly understood that a starting switch is not a branch circuit breaker and does not provide short-circuit protection, which must be taken care of by an approved protective device, as discussed in Chapter 14. Motor-starting switches, being mechanically closed, do not provide undervoltage protection.

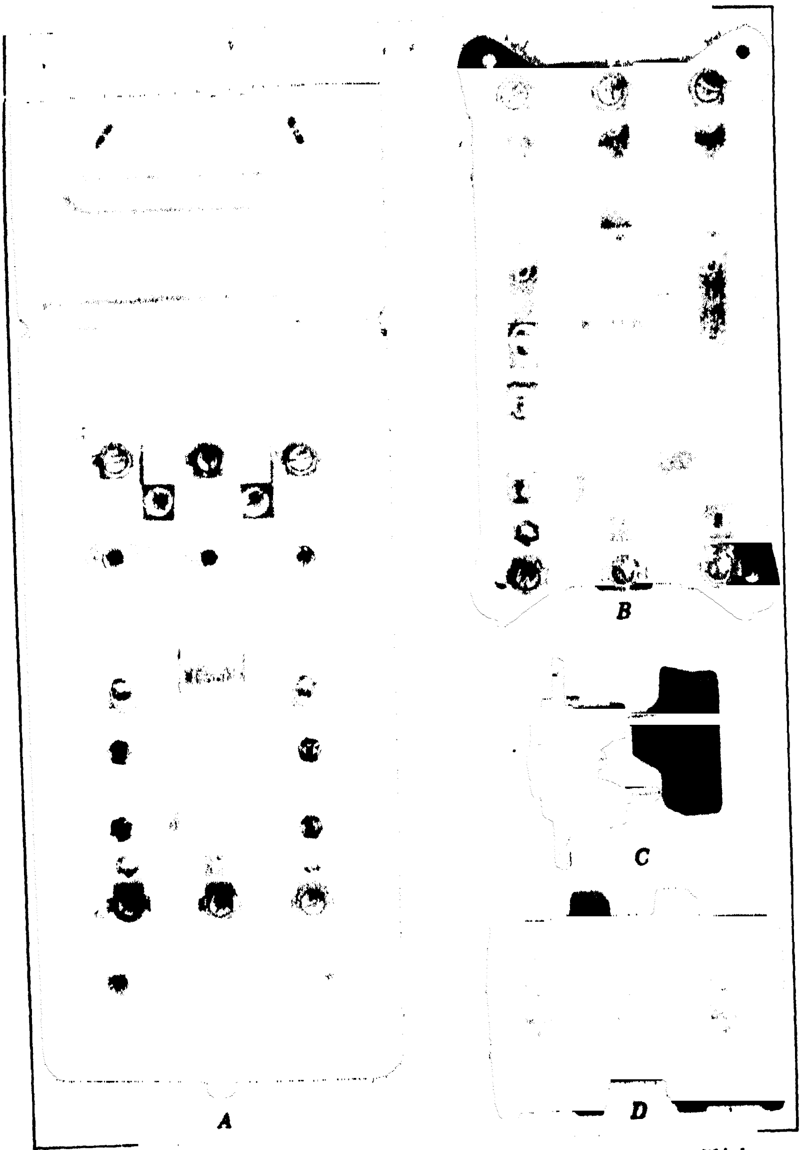


Fig. 287. Motor starting-switch rated 5 horsepower at 220 volts or 7½ horsepower at 440 volts. *A*. General view. *B*. Switch base. *C*. Solder-film overload relay. *D*. Movable contacts.

A typical starting switch is shown in Fig. 287. It is a three-pole device, with double break silver button contacts in each phase. The movable contacts are cradled in a molded block connected to a toggle mechanism. Thermal overload relays are of the solder type. After tripping, the relays are reset by moving the operating toggle to the off position, before reclosing the switch. After an overload, at least one minute must elapse before the relays can be reset. The starting switch shown is rated 3 hp at 110 volts, 5 hp at 220 volts, or 7.5 hp at 440 to 600 volts.

Starting Compensators

Manual starting compensators are auto-transformer starters for squirrel cage and synchronous motors. In connection with magnetic control, starting compensators are often found as starters for motor generator sets of adjustable-voltage systems.

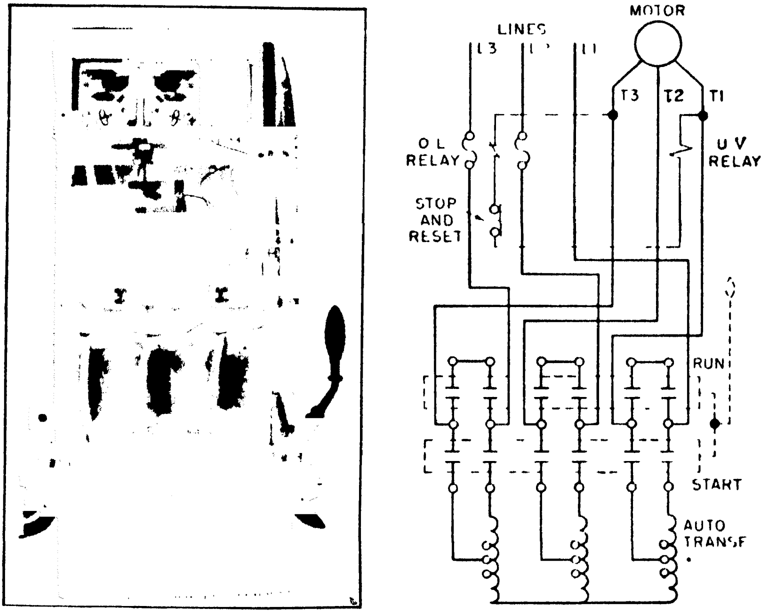


Fig. 288. Low-voltage starting compensator.

A typical low-voltage starting compensator is shown in Fig. 288. Two sets of contacts are arranged under oil. When the handle is moved to the start position, the start contacts close and connect the motor to the line through the auto-transformer. Moving the handle in the run position opens the start contacts and closes the run contacts, connecting the motor across full line voltage. A mechanical latch makes it impossible to close the run contacts before the start contacts have been closed. When the handle is released while in the start position, it snaps into the off position and prevents the operator from leaving the auto-transformer connected in the circuit.

The undervoltage relay opens a latch and drops out the compensator contacts upon loss of voltage. The motor is stopped by pressing the stop button, which de-energizes the undervoltage relay coil. Overload protection is afforded by a thermal overload relay, the contact of which is also connected in the undervoltage relay coil circuit. The stop button is so arranged mechanically that it also resets the overload relay.

In the compensator shown, the auto-transformer and the contact mechanism are assembled in a compact unit. For larger size motors, it is necessary to assemble the contacts and the auto-transformer as separate units. For large high-voltage motors, manually operated circuit breakers are used to establish the motor starting and running connections.

CHAPTER 17

GENERAL-PURPOSE CONTROLLERS

Whereas the preceding chapters of this book dealt with devices and elements of magnetic controllers, it is the purpose of the concluding chapters to present examples of complete controllers and control systems used in practice. In selecting controllers to be described in detail, an attempt has been made to choose some which are representative of present-day engineering practice and which illustrate the most commonly used types. The available field, from which a selection can be made, is very broad, and any discussion dealing with practical controllers must of necessity be incomplete, lest it exceed the space available within a book of convenient size. In making the selection, the author has attempted to pick subjects of interest to the majority of industrial control users.

General-purpose controllers are designed to start and stop motors found in the average industrial plant, where motors are usually applied on a continuous-duty basis and where no special performance characteristics are required. Such controllers are listed by manufacturers as *standard line controllers*. According to types of motors, the following general purpose controllers are in common use:

1. For d-c shunt and compound wound motors.
2. For a-c squirrel cage motors.
3. For a-c wound rotor motors.
4. For a-c synchronous motors.

CONTROLLERS FOR DIRECT-CURRENT SHUNT MOTORS[2]

Small motors, up to 1½ hp at 115 volts and 2 hp at 230 volts, have sufficiently high internal resistance to permit their starting at full voltage without exceeding the commutating limit. Starters for such motors are very simple, consisting of a line contactor, or a pair of reversing contactors, and an overload relay.

Larger motors must be started with resistance in series with the armature, in order to reduce the starting inrush current. Depending on the type of service required, the following forms of starters are available:

Non-reversing, starting.
Non-reversing, starting, with dynamic braking.
Non-reversing, starting, with speed control by field weakening.
Non-reversing, starting, with dynamic braking, with speed control by field weakening.
Reversing, starting, with dynamic braking.
Reversing, starting, with dynamic braking, with speed control by field weakening.

A standard line d-c shunt motor controller includes the following devices:

Line contactor or set of reversing contactors.
Set of accelerating contactors.
Means to sequence accelerating contactors.
Thermal overload relay.
Starting resistor, NEMA Class 135 or 136.
Dynamic braking contactor and resistor (if required).
Full-field or field-accelerating relay (on adjustable speed controllers only).
Field discharge resistor (only if field circuit is interrupted).

A line switch is generally not included as part of the controller, but a safety switch is often installed separately. Control circuit fuses may be included as an optional item, but usually they do not form part of standard line controllers. If the motor can be unloaded or subjected to an overhauling load, a field failure relay is added to prevent overspeeding because of loss of shunt field.

NEMA has standardized the size of line, reversing and accelerating contactors in terms of horsepower, as well as the number of accelerating points. Table 22 gives the NEMA ratings. The number of accelerating contactors used is one less than the number of accelerating

TABLE 22

NEMA RATINGS OF D-C MAGNETIC CONTROLLERS FOR CONTINUOUS DUTY

Open 8-Hour Rating in Amperes	*Horsepower Rating of Line, Reversing, and Final Accelerating Contactors*		*Number of Accelerating Points*
	115 Volts	*230 Volts*	
25	3	5	2
50	5	10	3
100	10	25	3
150	20	40	4
300	40	75	5
600	75	150	5

points, the first accelerating point being obtained with the line contactor closed and all accelerating contactors open. Intermediate accelerating contactors, which do not carry current continuously, are usually one size smaller than the main contactors. NEMA stipulates that the continuous current rating of intermediate accelerating contactors shall be not less than one sixth the maximum inrush current peak which such contactors would have to carry.

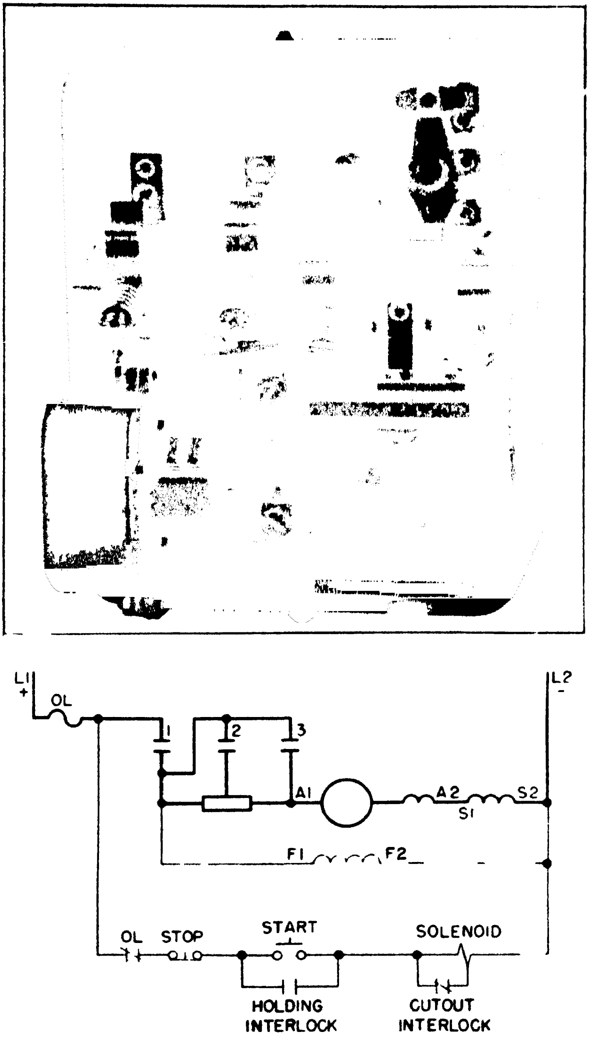


Fig 289 Mechanical time starter for small d-c motors

Mechanical Time Starter for Small Motors

A simple starter for motors up to 3 hp at 230 volts is shown in Fig. 289. It consists of a system of contacts, mounted on a shaft, and operated by a solenoid. When the start button is pressed, the solenoid coil is energized with part of its winding short-circuited. Line contact 1, which is equipped with blowout and arc chute, closes immediately and connects the motor to the line. A holding interlock

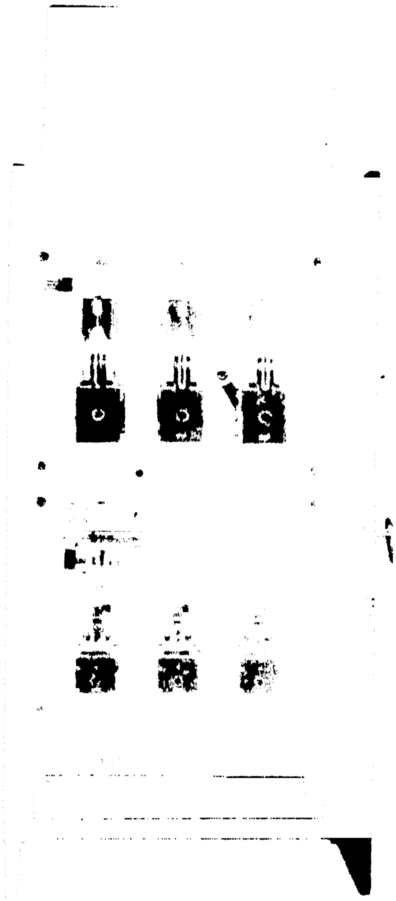


FIG. 290A Definite time d-c starter with dynamic braking.

seals around the start button, and a cut-out interlock inserts the remainder of the solenoid coil in the circuit. This connection obtains a high inrush current to close the solenoid, but this current is later reduced to a value which keeps the heating of the solenoid coil within the permissible limit, while still producing sufficient holding pull. A mechanical escapement type time delay mechanism is connected to the shaft carrying accelerating contacts 2 and 3, permitting these to close in time sequence as the energy stored in a spring by the solenoid closing action is gradually released. The total time of the accelerating sequence is adjustable.

A thermal overload relay protects the motor. When the motor is stopped by dropping out the solenoid and opening the contacts, the motor armature circuit provides a discharge path for the shunt field.

This simple and inexpensive starter is suited only for non-reversing starting service for constant-speed motors. It has the advantage of being small and compact. However, because of its many moving parts, it is inherently a device of comparatively low mechanical life, and it should not be used for frequent starting and jogging service.

Definite Time Starter with Dynamic Braking

Figure 290 is an example of a non-reversing starter for a larger constant-speed motor, with dynamic braking and with definite time acceleration. The starter is floor-mounted, NEMA type I enclosed, with the starting and dynamic braking resistor mounted on top of the

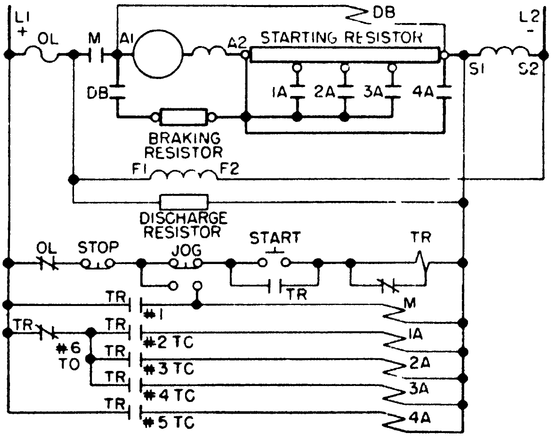


FIG. 290*B*. Connections of definite time d-c starter with dynamic braking. *M*. Line contactor. 1*A*, 2*A*, 3*A*, 4*A*. Accelerating contactors. *DB*. Dynamic braking contactor. *TR*. Accelerating relay. *OL*. Overload relay.

enclosure under a cover of perforated metal, which affords mechanical protection and ventilation. The contactors are standard shunt contactors. The line, dynamic braking, and final accelerating contactors have blowouts whereas the intermediate accelerating contactors have no blowouts.

Definite time sequence of accelerating contactors is obtained by timing relay *TR*, consisting of a solenoid and a shaft, which actuates a multiplicity of contacts. The turning of the shaft is retarded by an escapement type mechanical time delay device. The individual relay contacts are adjustable so that their closing and opening is staggered by definite time intervals. Thus the accelerating contactors close in time sequence. After contactor 4*A* has closed, contactors 1*A*, 2*A*, 3*A* are dropped out, which reduces coil heating and prevents their interrupting current when the motor is stopped.

Dynamic braking contactor *DB* is energized as soon as line contactor *M* closes. However, *DB* is prevented from closing by a mechanical interlock, as long as *M* is closed. As soon as *M* opens, *DB* closes, its coil being energized by the counter emf of the motor. *DB* stays closed until the motor has decelerated to a slow speed. In order to maintain the motor counter emf during the slow-down period, and to cause braking current to flow through the motor armature, the shunt field is connected across the line, and it stays energized when *M* opens. No discharge path is available through the armature circuit, and a discharge resistor (usually made of Thyrite) must be provided for protection of the field.

Jogging is possible by the use of a separate jog push button, which energizes the line contactor only, without energizing *TR* and any accelerating contactors. The jogging circuit is so arranged that it is impossible to seal in the line contactor when the jog push button is released suddenly. A separate jogging relay is unnecessary with this circuit.

Reversing Starter

For an example of a reversing starter with dynamic braking for an adjustable-speed motor, see Figs. 291 and 292. This starter includes definite time acceleration by means of accelerating contactors having an inherent time delay drop-out feature. Two accelerating contactors are provided, one for the forward and one for the reverse direction. The panel is enclosed in a ventilated type I wall mounted case, and the starting and braking resistor is mounted in the back of the base.

Pressing the forward push button energizes accelerating contactor *FA* which opens its main contact. Through an interlock on *FA*, forward contactors 1*F* and 2*F* are energized, and they are sealed in through an interlock of 1*F*. A normally closed interlock on 1*F* deenergizes the coil of contactor *FA*, which drops out with a time delay and short-circuits the starting resistor. Similarly, when the reverse push button is pressed, *RA* opens first, then 1*R* and 2*R* close, and *RA* drops out with a time delay. The forward and reverse push buttons are electrically interlocked through their respective back contacts.

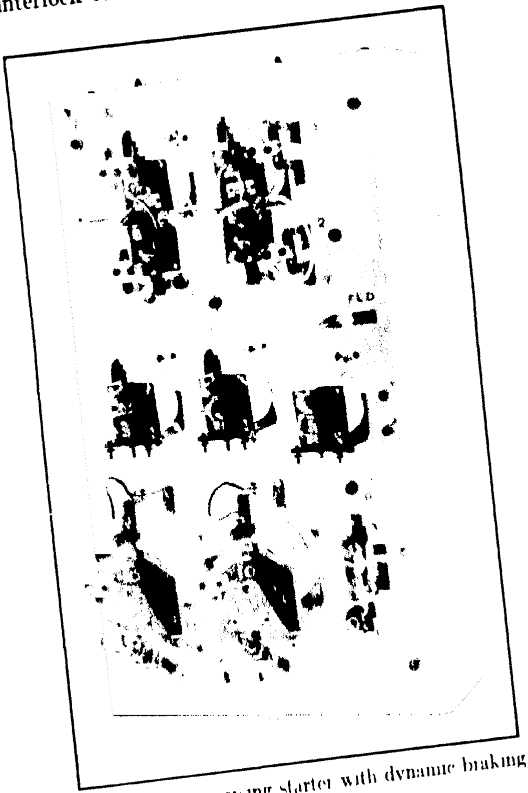


Fig. 291. D-c reversing starter with dynamic braking

Dynamic braking is obtained by normally closed contacts on contactors 1*F* and 2*R*, which connect the dynamic braking resistor in parallel with the motor armature when the stop button is pressed or the overload relay trips. To insure ample contact pressure on the normally closed contacts, 1*F* and 2*R* are equipped with holding coils which are energized by the counter emf of the motor.

Motor speed is controlled by a field rheostat, connected in series with the shunt field. To insure sufficient starting torque, the field rheostat is short-circuited by full-field contactor *FF* during starting. *FF* has two shunt coils. One coil is connected across the starting resistor. At the instant of starting, most of the voltage drop in the armature circuit is across the starting resistor; thus *FF* closes. When

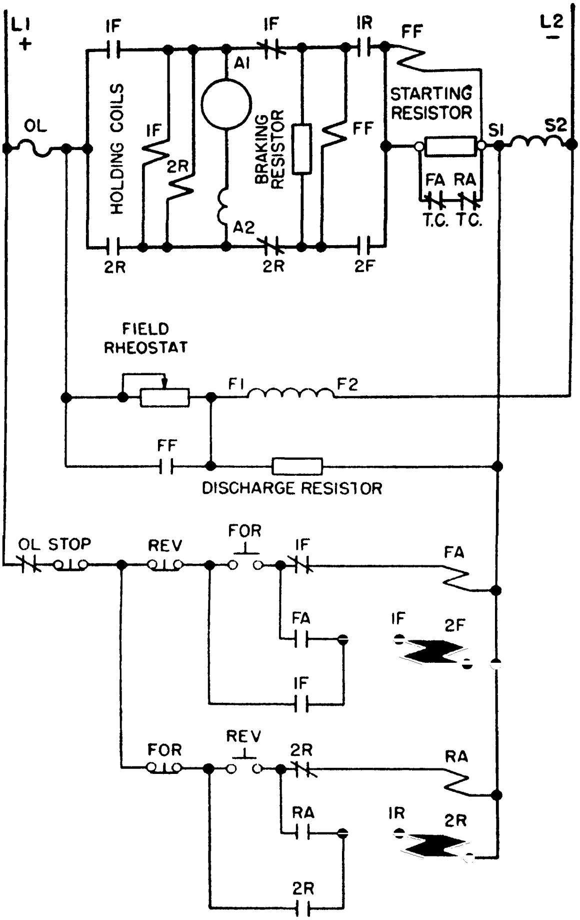


FIG. 292. D-c reversing starter with dynamic braking for adjustable-speed shunt motor. 1*F*, 2*F*. Forward contactors. 1*R*, 2*R*. Reverse contactors. *FA*. Forward accelerating contactor. *RA*. Reverse accelerating contactor. *FF*. Full-field contactor. *OL*. Overload relay.

the starting resistor is short-circuited, *FF* drops out and inserts the field rheostat. The second coil of *FF* is connected in the motor armature circuit in such a way that it is energized by the motor counter emf during dynamic braking. This arrangement insures that dynamic braking takes place with full field so that the motor develops maximum braking torque, regardless of the position of the field rheostat.

CONTROLLERS FOR ALTERNATING-CURRENT INDUCTION MOTORS

Standard line controllers for induction motors are generally understood to be starters. Speed-regulating controllers fall into the special class. Where close speed control is warranted, d-c drives predominate. Where many speed points are required on wound rotor motors, full-magnetic controllers are expensive, and drum switches, either hand or motor-operated, are often used for secondary resistor control. Thus the field of standard general-purpose a-c controllers narrows down to controllers for starting and stopping of motors.

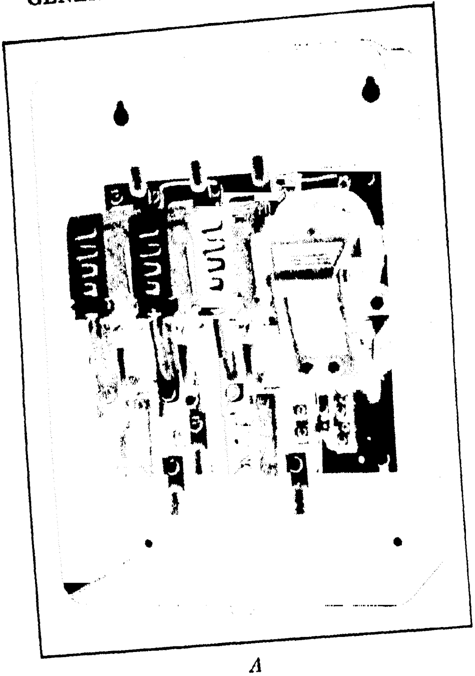
Controllers may be either non-reversing or reversing. Depending on the type of motor with which they are used and the method of starting employed, the following types of induction motor controllers are available:

Full-voltage starters for squirrel cage motors.
Reduced-voltage starters for squirrel cage motors.
  Primary resistor type.
  Reactor type.
  Auto-transformer type.
Secondary resistor starters for wound rotor motors.

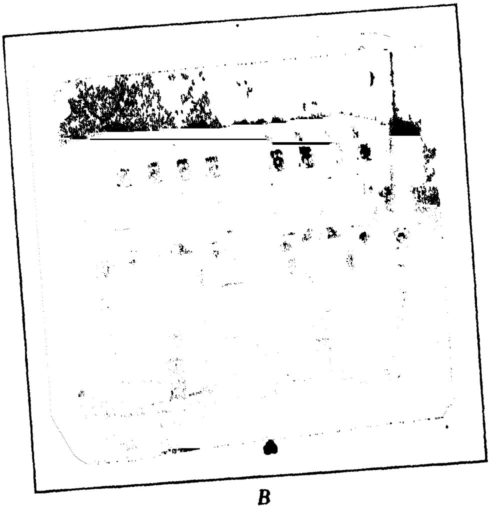
Full-Voltage Starters

Full-voltage starters consist of a line contactor, or a pair of reversing contactors, and thermal overload relays in two phases. They are enclosed in a standard NEMA case. Reversing contactors are mechanically interlocked, and electrical interlocking can be accomplished by using the back contacts of the reversing push buttons. Typical non-reversing and reversing full-voltage starters for low-voltage circuits are shown in Fig. 293.

Contactors used on such starters must be able to carry full-load motor current continuously and to interrupt the locked rotor current. Contactor ratings have been coordinated by NEMA with motor ratings, and Table 6 (page 178) applies. When motors are frequently



A



B

Fig. 293. A-c full-voltage starters *A* Non-reversing. *B*. Reversing.

jogged or stopped by plugging, the contactors must interrupt locked rotor current more frequently. For applications requiring jogging or plugging more frequently than five times per minute, NEMA recommends that contactors be selected in accordance with Table 23.

TABLE 23

NEMA RATINGS OF FULL-VOLTAGE STARTERS FOR FREQUENT PLUGGING AND JOGGING SERVICE

	Maximum Horsepower Rating					
	110 Volts		*220 Volts*		*440 and 550 Volts*	
Contactor Size	*Three-Phase*	*Single-Phase*	*Three-Phase*	*Single-Phase*	*Three-Phase*	*Single-Phase*
00	⅓	¼	½	⅓	½	
0	¾	½	1	¾	1	¾
1	2	1	3	2	5	3
2	5	2	10	5	15	7½
3	10	5	20	10	30	15
4	15		30		60	
5			75		150	
6			150		300	

As far as full-voltage starters are concerned, there is no inherent limitation to the size of motors with which such starters can be used. Whether or not a given squirrel cage motor can be started at full voltage depends primarily on the capacity of the power system and on rules established by the power company, and sometimes on the starting torque which the drive can stand. It is a motor application rather than a control problem.

High-voltage starters may be air break or oil-immersed. Air break contactors should always be used for motors which are started frequently, because of longer contact life. Oil-immersed starters may have to be used in hazardous locations. When oil immersion is not a necessity for safety reasons, it offers the advantage of smaller size than that of air break starters of equivalent rating. The ratings of high-voltage oil-immersed contactors, for use in starters, are standardized by NEMA in accordance with Table 24.

TABLE 24

RATING OF HIGH-VOLTAGE OIL-IMMERSED A-C STARTERS FOR INDUCTION MOTORS

8-Hour Ampere Rating	*Maximum Horsepower Rating*	
	2200–2300 Volts	*4000–4600 Volts*
100	350	
200	700	1250
400	1500	2500

Combination starters include not only motor protection but also short-circuit protection. In addition to contactors and overload relays, they contain air circuit breakers or fused line switches or, in the case of high-voltage starters, current-limiting fuses. Shown in Fig. 294 are low-voltage combination starters. The starter to the right includes an air circuit breaker with external operating handle, and the starter to the left a fused line switch.

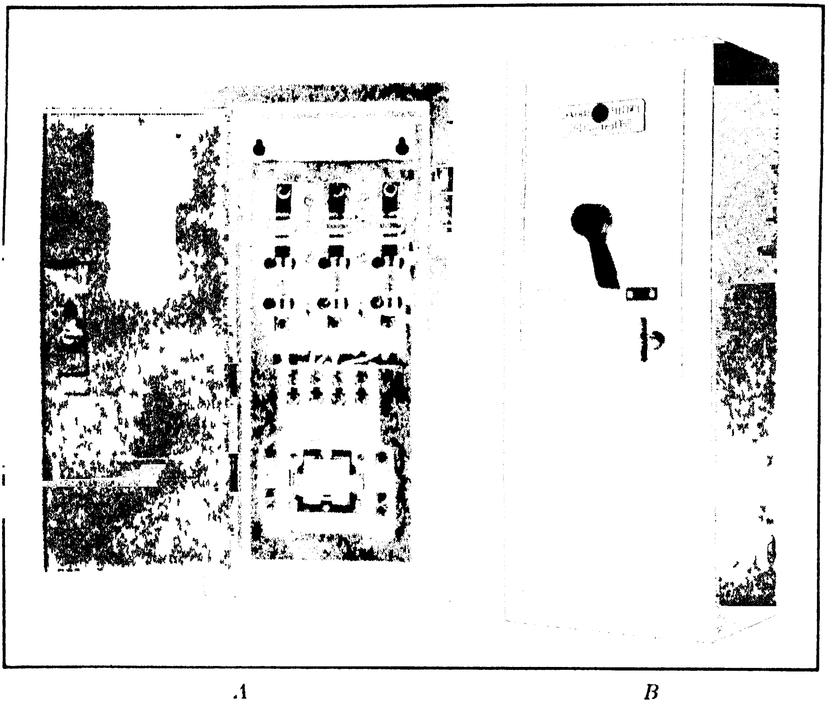


FIG. 294. A-c low-voltage combination starters. *A.* With fused knife switch, door open. *B.* With air circuit breaker, door closed.

Figure 295 is a front and back view of high-voltage combination starters. The current-limiting fuses in the upper compartment and the overload relay in the lower compartment are accessible from the front. The oil-immersed contactor, the tank of which can be lowered by a winch, is accessible from the back for inspection and maintenance.

Full-voltage starters for multi-speed squirrel cage motors contain necessary contactors and overload relays, the detailed arrangement and connections depending on the internal connections of the motor with which they are used. See Fig. 66 for basic motor circuits and Table 7 (page 179) for contactor ratings.

Standard full-voltage starters are also used as line contactors for wound rotor motors on semi-magnetic controllers, which include manually or motor-operated drum switches for the secondary control. Contactor ratings are the same as for squirrel cage motors as given in Table 6 (page 178).

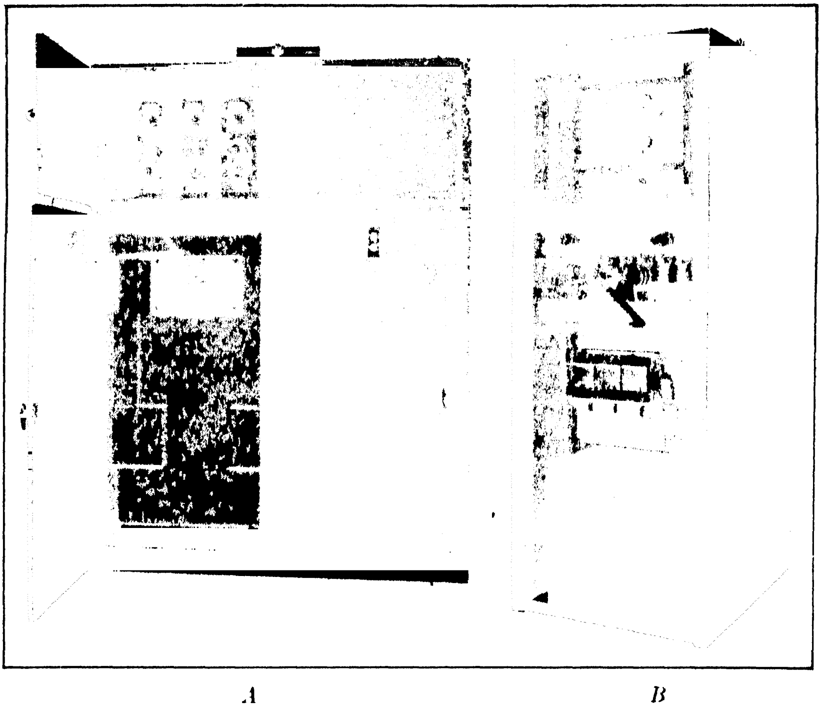


FIG. 295 A-c high-voltage combination starters *A* Front view *B* Back view

Reduced-Voltage Starters

Reduced-voltage starters include the following devices:

Start contactors (one or several).
Run contactor.
Timing means to sequence from start to run connections.
Thermal overload relay.
Means to reduce motor terminal voltage (resistor, reactor, autotransformer).

The rating of contactors, used on such starters, is the same as given in Table 6, except that NEMA recognizes a rating standard only in sizes 1 and larger. The start contactor of starters with a single accelerating step is of the same size as the run contactor, up to size 4. On larger-size starters, the start contactor may be one size smaller than the run contactor. If more than one starting step is used, accelerating contactors are selected so that their open 8-hour rating is not less than one sixth of the peak current they have to carry.

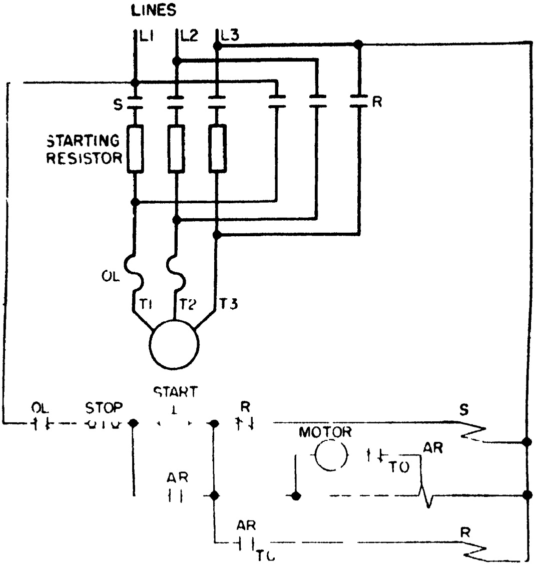


FIG. 296. A-c primary resistance starter. *S*. Start contactor. *R*. Run contactor. *AR*. Accelerating relay. *OL*. Overload relay.

Figure 296 is a typical elementary diagram of a primary resistance starter. When the start button is pressed, start contactor *S* and accelerating relay *AR* close. The motor is connected to the line through the starting resistor. Relay *AR* is a motor-driven time relay, and after it has timed out, it closes its timing contact. Run contactor *R* then closes, connecting the motor to full line voltage. Contactor *S* is dropped out through a normally closed interlock on *R*, which reduces the coil heating of *S*. Contactors *R* and *S* overlap, and during the transition period the motor stator circuit is not interrupted. Reactor starters are built like resistance starters, except that a reactor is substituted for the starting resistor. Figure 297 is a view of a reactor starter, enclosed in a type I case. Both the start and the run contactors are equipped with blowouts. Should the stop push button be pressed or should the overload relay trip during the starting period, the start contactor would be called upon to interrupt the motor circuit under power.

Auto-transformer starters are similar in appearance, except that a transformer is substituted for the reactor and the start contactor is equipped with five power contacts. See Fig. 298 for a typical elementary diagram. The two extra poles on the start contactor are necessary to isolate the transformer while the run contactor is closed to avoid circulating currents in the transformer winding. Another possible connection is to place the two extra poles of *S* in the neutral of the transformer, as is shown in Fig. 242. There is one important detail in the control connections in which both Fig. 242 and Fig. 298 differ from Fig. 296. The start contactor must drop out before the run contactor is closed, to avoid a high current surge and corresponding high mechanical stress in the transformer winding, which may cause damage to the transformer. When the start push button is pressed, accelerating relay *AR* is energized, and at the same time start contactor *S* closes. The motor is connected to a reduced voltage through a tap on the auto-transformer. When *AR* has timed out, contactor *S*

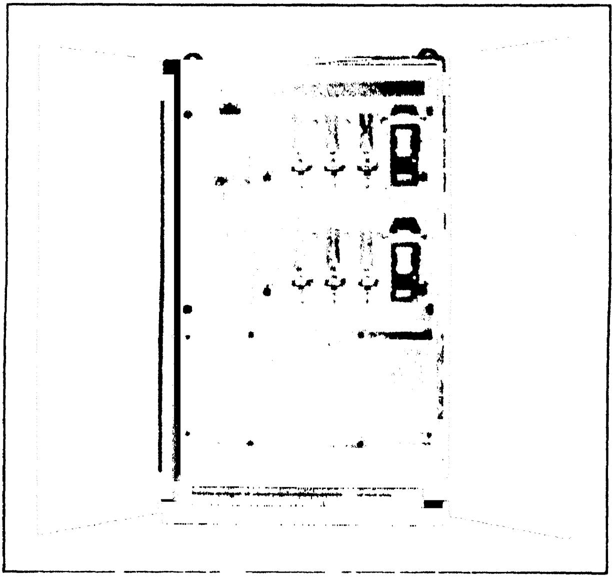


FIG. 297. A-c primary reactor starter

is first dropped out, and then contactor *R* closes, connecting the motor to full line voltage.

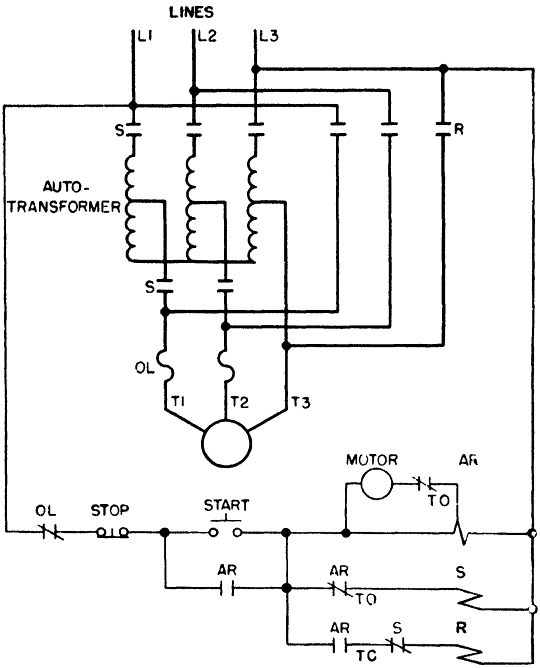


FIG. 298. Auto-transformer starter. *S*. Start contactor. *R* Run contactor. *AR*. Accelerating relay. *OL*. Overload relay.

For high-voltage applications, either air break or oil-immersed contactors can be used, and current-limiting fuses may be added for short-circuit protection.

Wound Rotor Motor Starters [4]

Wound rotor motors are started with resistance connected in the secondary circuit. Starters may be non-reversing or reversing. A standard general-purpose starter includes the following:

Line contactor or pair of reversing contactors.
A set of accelerating contactors.
A set of accelerating relays.
Thermal overload relay.
Starting resistor.
Control fuses as optional item.

Line or reversing contactors are rated on the same horsepower basis as for full-voltage starters, except that NEMA recognizes a standard only in sizes 1 and larger. Final accelerating contactors are selected for carrying the actual motor secondary current. If two-pole contactors are used open-delta-connected, the motor secondary current should not exceed the open 8-hour rating of the contactor. If triple-pole contactors are used delta-connected (see Fig. 120), they are applied on the basis of 150 per cent of their 8-hour rating. Intermediate accelerating contactors should have a rating of not less than one sixth of the maximum current peak they have to carry. It is customary to make intermediate accelerating contactors one size smaller than the final accelerating contactor. Since they do not interrupt current, they are not equipped with blowouts.

No standard has been established by NEMA on the number of accelerating steps to be used. Table 25 gives the number of accelerating steps customarily used on general-purpose starters. The number of accelerating contactors is one less than the number of steps indicated.

TABLE 25

NUMBER OF ACCELERATING STEPS CUSTOMARILY USED ON WOUND ROTOR MOTOR STARTERS

Maximum Horsepower	*Number of Accelerating Steps*
15	2
75	3
150	4
300	5
1000	6

Typical low-voltage starters are shown in Fig. 299. Starter *A* is used with motors up to 75 hp. It is enclosed in a type I wall-mounted case. The starting resistor is mounted in the back of the base. The panel can be tilted forward to gain access to the back of the base and the resistor. Starter *B* is suitable for use with motors up to 150 hp. It is floor-mounted, enclosed type I, with resistor mounted on top of the case.

Figure 300 is the elementary diagram of a four-point starter. Definite time relays are used in this case to control the closing of the accelerating contactors. Other types of accelerating relays can be used, such as current limit or frequency relays, as is explained in Chapter 12. The accelerating relays shown in the diagram are of the magnetic time delay drop-out type with d-c coils, and each relay is connected to its own rectifier. Whether individual rectifiers or a common bank of rectifiers for all relays is selected is primarily a matter of economics and should be studied for each panel design. The following circuit details are to be noted. Normally open interlocks on the accelerating relays are connected in series with the pick-up circuit of line contactor *M*. Thus failure of any relay coil or rectifier prevents the line contactor from closing. After the start push button has been pressed and line contactor *M* has closed, accelerating contactors 1*A*, 2*A*, 3*A* close in time sequence, as governed by relays 1*AR*, 2*AR*, 3*AR*. When 3*A* closes, contactors 1*A* and 2*A* are dropped out and relay 2*AR* and 3*AR* coil circuits are opened, to reduce coil and rectifier heating.

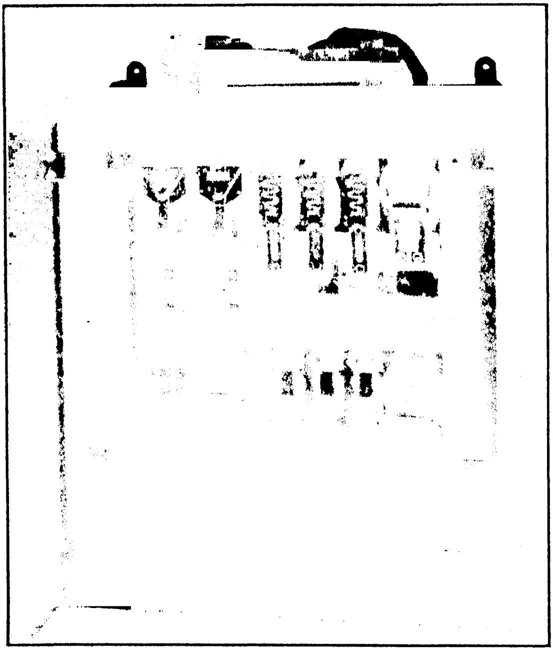


FIG. 299*A*. Low-voltage starters for wound rotor induction motors. Wall-mounted.

High-voltage starters may be built with air break or oil-immersed primary contactors. A typical high-voltage air break type reversing starter is shown in Fig. 301. The left-hand panel section contains the high-voltage reversing contactors, which are equipped with d-c magnets. Potential interlocking relays are mounted above the contactor magnets. Current-limiting fuses in the top compartment provide short-circuit protection. The right-hand section contains the accelerating contactors, accelerating relays, overload relays, and several control relays for initiating automatic plugging to bring the motor to a quick stop. The starting resistor is mounted inside the panel enclosure above the secondary control section.

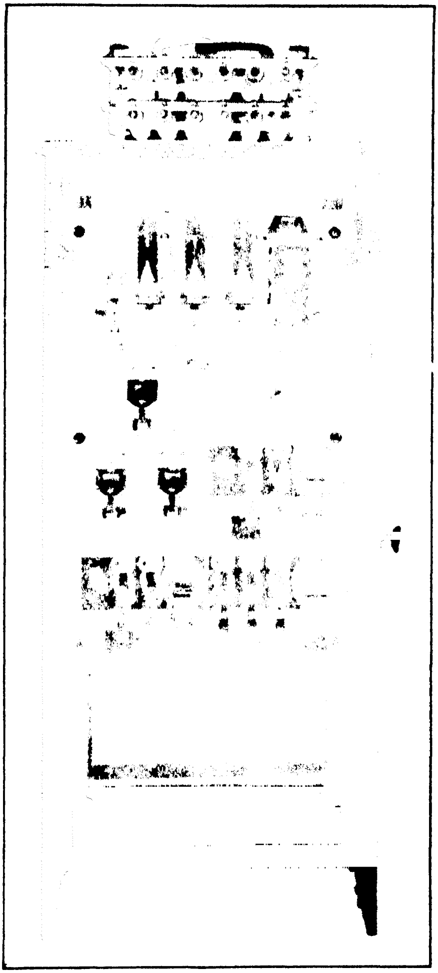


FIG. 299B. Low-voltage starters for wound rotor induction motors. Floor-mounted.

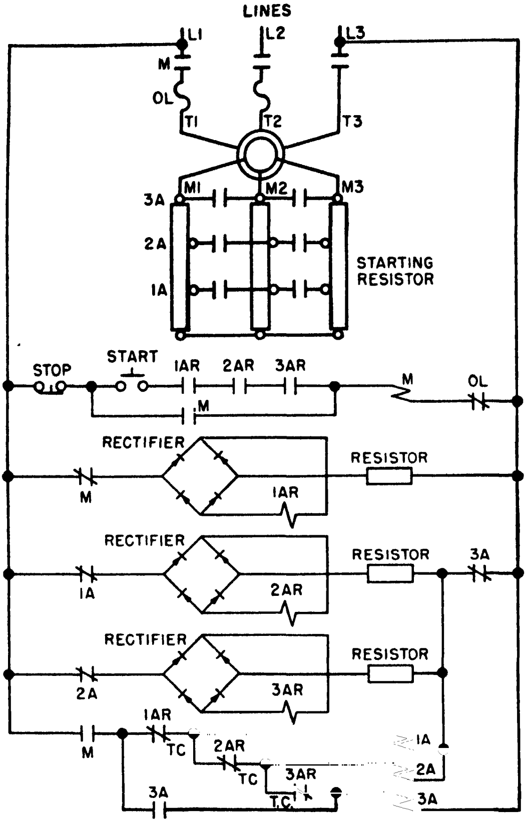


FIG. 300. Definite time starter for wound rotor induction motors. *M*. Line contactor. 1A, 2A, 3A. Accelerating contactors. *1AR, 2AR, 3AR*. Accelerating relays. *OL*. Overload relay.

CONTROLLERS FOR SYNCHRONOUS MOTORS[4]

Synchronous motors are equipped with a squirrel cage winding in the rotor pole faces, and they are started like squirrel cage induction motors, as explained in Chapter 3. Therefore, most synchronous motor controllers include equipment to connect the stator to the line, which is the equivalent of a full-voltage or a reduced-voltage starter. Large synchronous motors are sometimes started by first connecting part of the armature winding and then the full armature winding to the line. Synchronous motor starters differ from induction motor starters by the addition of control devices necessary to apply d-c exci-

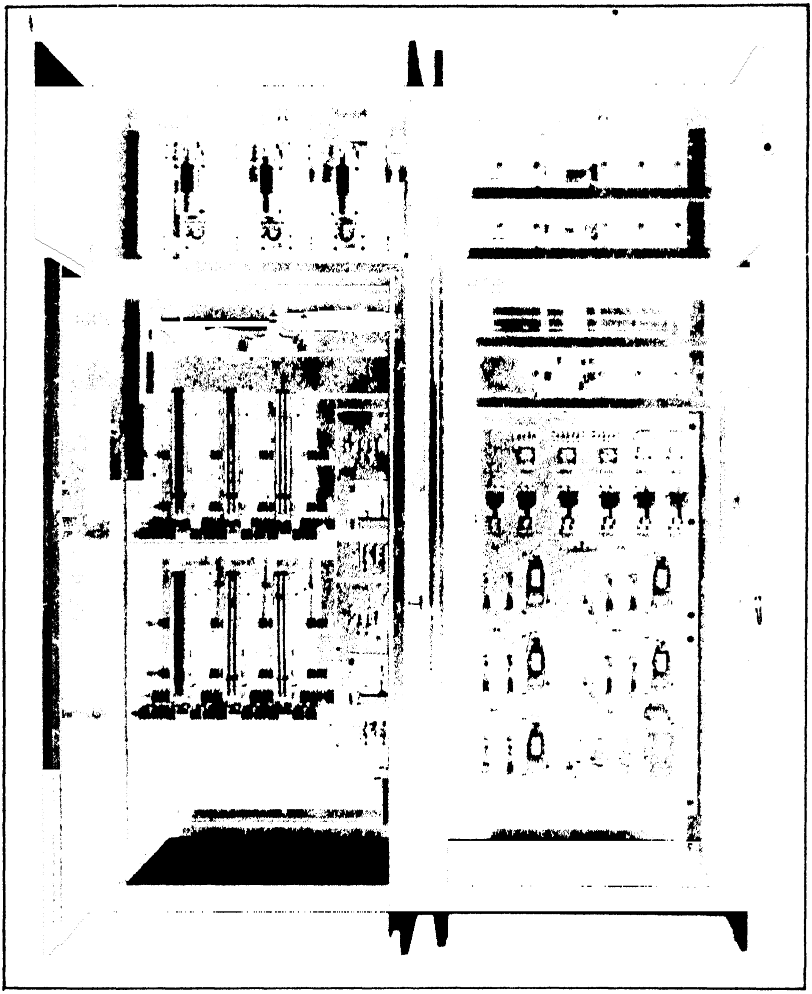


Fig. 301. High-voltage reversing starter for wound rotor induction motors

tation to the motor field. Other devices may be added (or may be included as an inherent part of the field application devices) to remove field excitation when the motor pulls out of synchronism, and to protect the squirrel cage winding while the motor is operating out of synchronism.

A synchronous motor starter includes, in addition to the full-voltage or reduced-voltage or part-winding starting equipment, the following devices:

Field contactor, which closes to connect the field winding to a d-c source and, when dropped out, connects the field winding to a discharge resistor.

Means for energizing the field contactor at the correct point of the starting cycle and for removing field excitation when the motor pulls out of step, usually consisting of one or several relays.

Field discharge resistor.

Optional items are:

Field rheostat or tapped field resistor for adjustment of the field current.

Line ammeter.

Field ammeter.

Protective relay to prevent overheating of the squirrel cage winding.

In Chapter 3 it is explained that the point in the starting cycle, at which field excitation is applied, has an important bearing on the torque available for pulling the motor in synchronism. Various systems have been developed to control the closing of the field contactor, and in the following paragraphs several typical methods of field application are described. For the sake of simplicity, all diagrams are drawn for full-voltage starting of a low-voltage motor. Any type of reduced-voltage starter may be substituted without affecting the field application circuits.

When field excitation is obtained from a constant-voltage d-c source, independent of the motor, the field resistor or rheostat is connected in series with the motor field winding. When an exciter is used which is driven by the motor, the rheostat is connected in the exciter field circuit, and the motor field current is adjusted by varying the exciter voltage. During starting, the exciter field rheostat is short-circuited in most cases to obtain a faster build-up of exciter voltage.

Field Application by Timing Relay

Starting a synchronous motor with no load or with a very light load, which occurs, for instance, on motor generator sets, does not require any special precautions concerning the rotor position, relative to the stator, at which field excitation is applied. The motor accelerates as an induction motor to a low minimum slip, and sufficient synchronizing torque is developed at any rotor position to pull the motor into synchronism. A very simple control system is obtained if the closing of the field contactor is made a function of the time elapsed after the closing of the line or run contactor, as long as sufficient time is allowed to accelerate the motor to minimum slip.

Refer to Fig. 302. An interlock on line contactor *M* energizes a motor-driven timing relay *FR*, the time-closing contact of which energizes field contactor F, which connects the motor field to the d-c

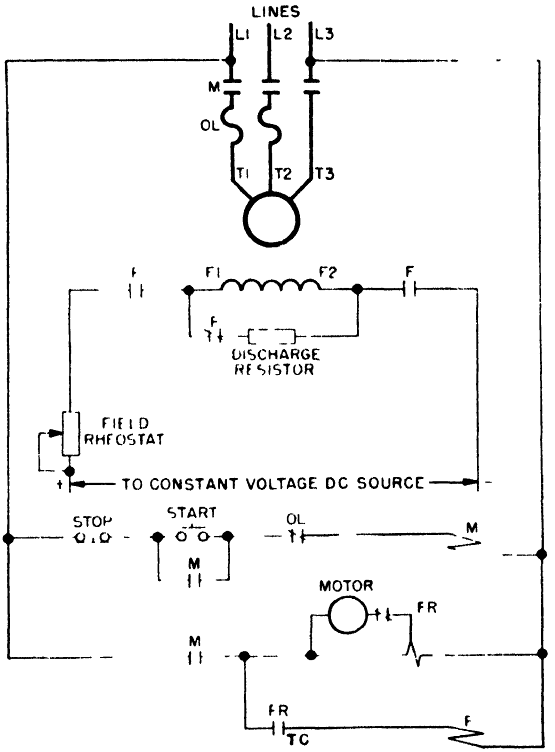


FIG. 302. Synchronous motor starter with definite time field application. *M*. Line contactor. *F*. Field contactor. *FR*. Field relay. *OL*. Overload relay.

source and disconnects the field discharge resistor. With the control circuits shown, the field excitation is not removed immediately when the motor pulls out of step on account of an overload. The regular overload relay *OL* must be relied upon to disconnect the motor from the line and the field from the d-c source, which may not protect the squirrel cage winding, usually designed for starting duty only, against overheating. Control devices, which disconnect the motor from the line as a function of the heating of the squirrel cage winding, add valuable protection.

Field Application by Slip Frequency Relay

When the stator of a synchronous motor is connected to the line, a voltage is induced in the field winding, the frequency of which is equal to the slip frequency. At standstill it is equal to line frequency, and at synchronism it is zero. When a synchronous motor is started under load, the change in frequency of the induced voltage can be used to determine the proper instant at which to apply d-c field excitation.

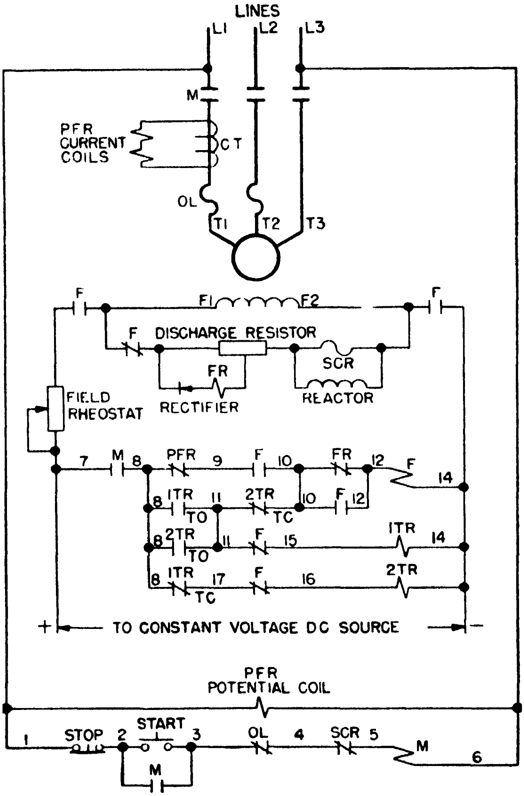


FIG. 303. Synchronous motor starter with slip frequency field application. *M*. Line contactor. *F*. Field contactor. *FR*. Field relay. *PFR*. Power factor relay. *OL*. Overload relay. *SCR*. Squirrel cage protective relay. *1TR, 2TR*. Definite time relays.

One application of the slip frequency principle is shown in Fig. 303. As long as field contactor *F* is dropped out, the motor field winding is connected to a discharge resistor, and a-c current flows through the resistor, the frequency of which is equal to slip frequency. Field relay *FR* is connected across a portion of the resistor through a rectifier. This relay is a d-c relay of the same construction as shown in Fig. 108. Its coil is copper-jacketed. Through the rectifier, half-wave current pulses flow through the relay coil as indicated in Fig. 304. As long as the slip frequency is high, the current pulses are close together. The relay stays picked up during the period between half cycles. As the time between half cycles becomes longer and longer, a point is reached at which the period between half cycles becomes longer than the adjustable drop-out time of the relay. Thus the relay recognizes that, when it drops out, the slip frequency has dropped to a sufficiently low value to permit closing of the field contactor. With the rectifier connected as shown, negative half cycles of current pass through the relay coil. Therefore, drop-out and field application occur while the voltage induced in the field winding is in a positive direction. As a result, as explained in Chapter 3, field application occurs at a favorable angle, provided the timing of relay *FR* is adjusted correctly so that field application takes place at a displacement angle beyond 180 degrees.

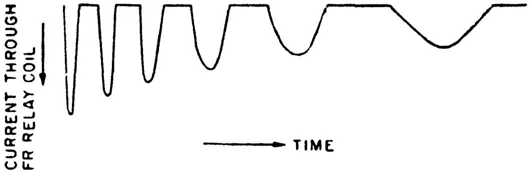


Fig. 304 Current through coil of relay *FR* prior to synchronizing.

The control sequence of field application is as follows. When line contactor *M* closes, relay *FR* is energized and opens its contact 10–12. Through interlock 7–8 on *M*, relay 2*TR* is energized, and it closes its contact 8–11 and opens its contact 11–10 instantaneously. The coil of relay 1*TR* is energized through 2*TR* contact 8–11. Relay 1*TR* closes its contact 8–11 and opens its contact 8–17 instantaneously, thus sealing in 1*TR* and de-energizing the coil of 2*TR*. After a time delay, contact 8–11 on 2*TR* opens, and contact 11–10 closes. As the motor accelerates to minimum slip, relay *FR* drops out, closes its contact 10–12, and causes contactor *F* to close. The field is then connected to the d-c source, and the discharge resistor is disconnected. Normally closed interlocks 11–15 and 17–16 on *F* open and disconnect 1*TR* and 2*TR* relay coils. 1*TR* drops out with a time delay and opens its contact 8–1. However, when the motor pulls in synchronism, relay *PFR* closes its contact 8–9 and establishes a holding circuit for contactor *F*.

Field Removal under Overload

If a sudden overload is applied to the motor, which exceeds its pull-out torque, the motor falls out of step. If field excitation is kept on the motor, it stalls, drawing a heavy armature current, and it is unable to resynchronize, even if the overload disappears. However, if field excitation is removed after the pull-out occurs, the motor operates as an induction motor, and if the overload disappears, it accelerates again to minimum slip and resynchronizes.

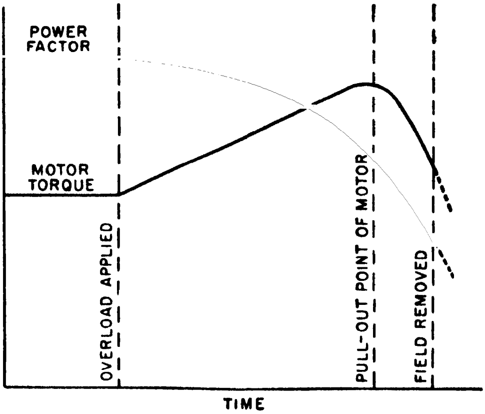


FIG. 305. Effect of overload on torque and power factor of synchronous motor

The power factor of the armature current can be used to initiate field removal upon pull-out. What happens to the power factor when an overload is applied to the motor is illustrated in Fig. 305. As long as the motor develops its normal torque, the power factor is high. When the overload is applied and the motor torque increases, the power factor decreases, at first slowly, but when pull-out occurs, it decreases rapidly.

Power factor relay *PFR* responds to the phase angle of the motor armature current. This relay is similar in construction to the phase failure relay shown in Fig. 130. Its magnet has a set of current and potential coils, and the torque exerted on the vane-shaped armature is a function of the magnitude as well as the phase angle of the current. A lever arm and weights, attached to the armature, permit adjusting the point at which the relay opens its contact.

With the motor operating in synchronism, and the power factor being high, the contact of *PFR* stays closed, even though the armature current may vary over a wide range. When the motor pulls out of step, which means that the current is high and the power factor is low, *PFR* opens its contact and drops out contactor *F*, which disconnects the field from the d-c source and reconnects the field to the discharge resistor. Relay *2TR* coil is energized and relay *FR* opens its contact When the overload disappears again, the motor reaccelerates to minimum slip, and field is applied again through the same relay sequence as described above for a start from rest.

Protection of Squirrel Cage Winding

While the motor operates in synchronism, and at a constant load angle, no voltage is induced in the squirrel cage winding, no current flows in it, and no heating takes place. However, during operation out of synchronism, an a-c current of slip frequency flows in the squirrel cage winding, which causes heating. Since the squirrel cage winding is designed for starting duty only, its heating capacity is limited, and it bears no relation to the heating capacity of the armature winding. If prolonged operation out of synchronism occurs, either during a start against an overload or after a pull-out, the squirrel cage winding is likely to heat much faster than the armature winding. Generally, the thermal overload relay, which is selected to protect the armature winding, does not afford protection to the squirrel cage winding.

Squirrel cage protective relay *SCR* is used to protect the squirrel cage winding. It is a thermal overload relay, having a resistance type heater element. It may be either a separate relay or a third element of overload relay *OL*. The heater of relay *SCR* is connected in series with the discharge resistor. During operation out of synchronism, current flows through the heater, the frequency of which is equal to slip frequency and the magnitude of which is proportional to slip frequency. In parallel with the heater of *SCR* there is connected a small reactor which has the following purpose. The voltage induced in the squirrel cage winding is proportional to slip frequency, and the current flowing is determined by the impedance of the winding, which is composed of resistance and reactance. Reactance changes with frequency. The reactance of the reactor is chosen so that the ratio of its reactance to the combined resistance of the *SCR* heater and the reactor winding is the same as the ratio between reactance and resistance of the squirrel cage winding. At any slip frequency, the heating of *SCR* relay due to the I^2R losses in its heater is a replica of the heating of the squirrel cage winding due to its I^2R losses. Thus relay *SCR* can be so selected that it trips before the squirrel cage reaches an excessive temperature.

Field Application by Current-Time Relay

While the field application method just described depends on changes occurring in the rotor circuit during the starting cycle, the current-time method of synchronization makes use of the change in stator current which occurs while the motor accelerates to minimum slip. Figure 306 is an elementary diagram of a complete controller, and field relay *FR*, which governs the closing of field contactor *F*, is shown in a schematic manner in the lower left-hand corner. This relay has two plungers and an armature, which is constructed like a walking beam and is not restrained by any springs. The plungers are energized by three coils. Two of the coils, *OSP* and *LO*, are energized by the motor armature current through a current transformer. The third winding *CL* is a shunt winding, energized from the control source and wound so that its action opposes that of coil *LO*. Relay contacts *a* and *b* are opened and closed by the walking beam armature. In conjunction with relay *FR* is used a timing relay *TR*, which is of the magnetic time delay drop-out type. A capacitor and high ohm resistor *A* determine the time delay. Low ohm resistor *B* effects rapid charging of the capacitor. This relay has three separate armatures, each carrying a contact (*a*, *b*, *c*) so that the timing of each contact can be adjusted individually.

When the start button is pressed, relay 1*CR* closes, seals itself in, and energizes line contactor *M*. The starting inrush current of the motor flows through coils *LO* and *OSP* of relay *FR*. Coil *LO* pulls down the right-hand plunger and coil *OSP* pulls up the left-hand plunger so that relay contacts *FR*(*a*) close and contact *FR*(*b*) opens. After a slight time delay, the interlocks on contactor *M* close. Relay *TR* is energized, opens contact *TR*(*a*), and closes contacts *TR*(*b*) and *TR*(*c*). Coil *CL* of relay *FR* is then energized, and its pull opposes that of coil *LO*; but with a high starting current flowing, the right-hand plunger does not change its position. Coil *OSP* of *FR* is short-circuited. The left-hand plunger drops down, but the walking beam armature stays in its previous position, that is, contact *FR*(*a*) stays closed and contact *FR*(*b*) stays open. With increasing motor speed the current through *LO* coil decreases, and when the motor current has dropped to approximately 175 per cent of normal current, the pull of coil *CL* overcomes the pull of coil *LO*. The right-hand plunger of relay *FR* is pulled up, contacts *FR*(*a*) open, and contact *FR*(*b*) closes.

The coil of relay *TR* is de-energized and starts timing, as the coil current discharges through the capacitor and resistor *A*. The relay armatures drop out in time sequence, and contact *TR*(*a*) closes first, causing contactor *F* to close and apply field excitation. After a further time delay, so adjusted that the synchronizing current surge in the motor armature has decayed, contacts *TR*(*b*) and *TR*(*c*) open. Relay *FR* is then in the following condition. Coil *CL* is de-energized, coil

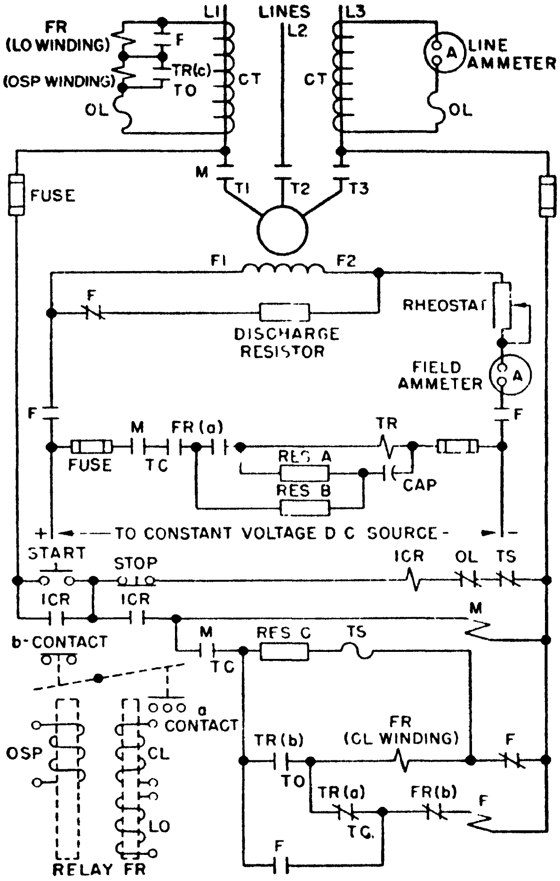


FIG. 306. Synchronous motor starter with current-time field application. *M*. Line contactor. *F*. Field contactor. *FR*. Field relay. *TR*. Definite time relay. *TS*. Thermal relay. *OL*. Overload relay. 1*CR*. Control relay. (Courtesy Cutler-Hammer, Inc.)

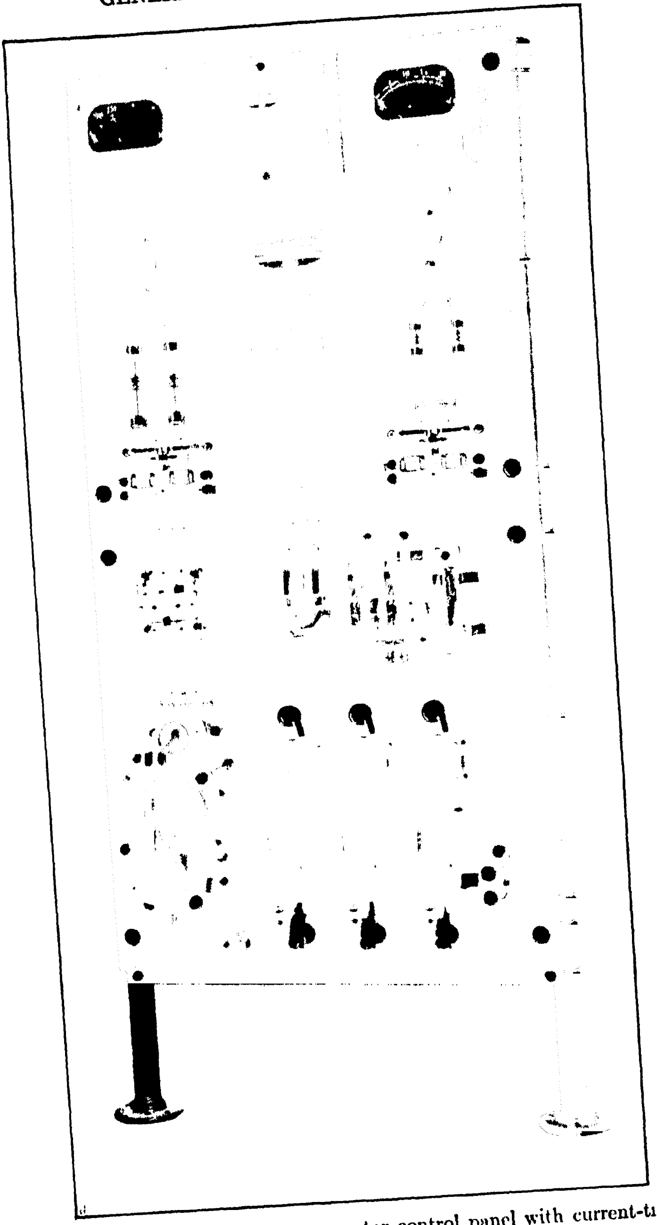


FIG. 307. Full-voltage synchronous motor control panel with current-time field application. (Courtesy Cutler-Hammer, Inc.)

LO is short-circuited by an interlock on *F*, and the right-hand plunger drops. *OSP* coil is reinserted, but, with normal motor current flowing, its pull is insufficient to lift the left-hand plunger, and relay contacts stay as they were, that is, *FR(a)* open and *FR(b)* closed, thus completing the synchronizing control sequence.

When the motor pulls out of synchronism on account of an overload, the resultant increase in armature current causes *OSP* coil of relay *FR* to lift the left-hand plunger, so that contact *FR(a)* closes and contact *FR(b)* opens. Contactor *F* drops out, removes field excitation, and the motor operates as a squirrel cage induction motor. The condition of the control circuits is the same as for a start from rest. If the overload is removed and the motor reaccelerates, the synchronizing sequence described above is repeated, and the motor is resynchronized. To avoid overheating of the squirrel cage winding, relay *TS* is provided. It is a thermal overload relay, the heating element of which is connected across the control source through resistor *C*, as long as contactor *F* is dropped out, that is, as long as the motor operates out of synchronism. Its tripping time is selected so that it is expected to open its contact and drop out *M* before the squirrel cage winding attains a dangerously high temperature.

Figure 307 is a view of an open type synchronous motor controller with current-time synchronization. In the top row of devices are line and field ammeters and between them a box containing relays *FR* and *TR*. Below on the top base are control fuses, field rheostat handle, and thermal relays *TS* and *OL*. The bell-shaped devices below the meters are capacitors used with relay *TR*. The lower base contains control relay 1*CR*, field contactor *F*, and line contactor *M*.

Field Application by Slip Cycle Impedance Relay

In Fig. 94 is indicated how the armature current of a synchronous motor varies during the starting period. While the motor operates out of synchronism, the current undergoes a periodic variation at slip frequency, both in magnitude and in phase angle. Thus during a slip cycle the motor impedance varies on account of saliency. A relay which would respond to the periodic change in motor impedance could determine the angular position of the rotor poles with respect to the stator flux poles during a slip cycle and cause field excitation to be applied at a favorable angle, as illustrated in Fig. 96.

Figure 308 shows a slip cycle impedance relay used to control application of field excitation. The upper figure is a view of the relay, with cover removed, whereas the lower one is an elementary diagram of its internal connections. The relay is based on the induction prin-

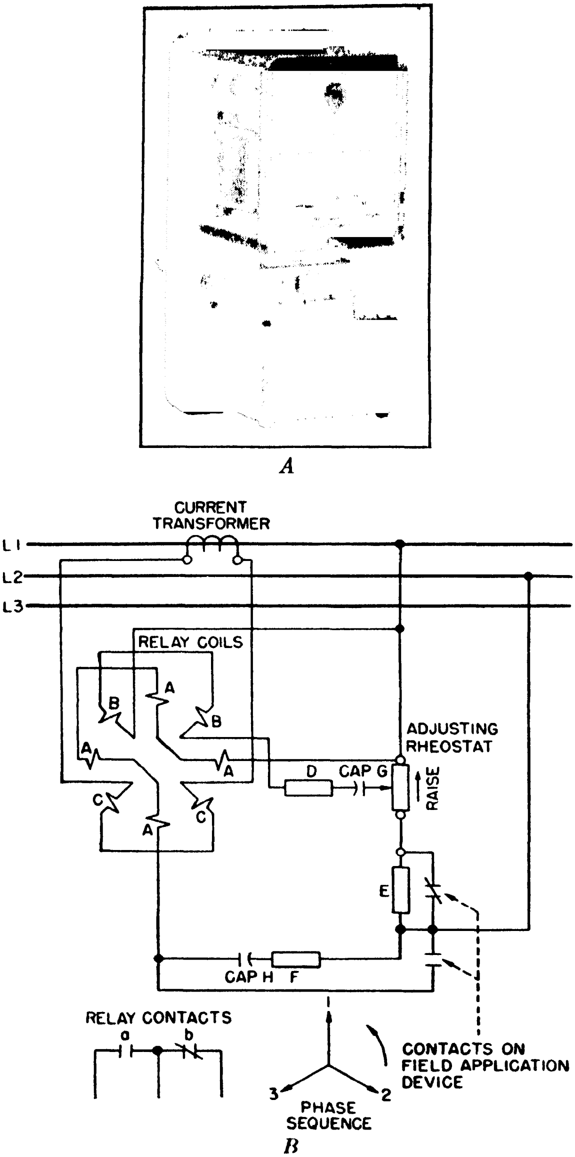


FIG. 308. Slip cycle impedance relay. *A*. View of relay with cover removed. *B*. Internal relay connections.

ciple, in fact, it is a miniature split-phase single-phase motor. It consists of a shaft upon which is mounted a cup-shaped aluminum rotor operating in the air gap of a magnetic structure which carries the operating coils. A set of movable contact tips mounted on an arm attached to the shaft operates between two stationary tips mounted on the molded frame. The relay element, together with auxiliary resistors and capacitors, is mounted on a molded base. The magnetic structure has eight laminated poles projecting inward and arranged symmetrically around a central magnetic core fixed to the frame. Two separate sets of potential coils and one set of current coils are assembled on the poles. In the angular air gap between the poles and the central core, the cylindrical portion of the cup-shaped rotor turns freely.

The relay coils are arranged in three groups, potential coils *A* and *B* and current coils *C*. The interaction of coils *A* and *B* produces a torque in the direction to close relay contact *a* and to open contact *b*. The interaction of coils *A* and *C* produces a torque in the direction to open contact *a* and to close contact *b*. Contact *a*, when closed, energizes the device applying field excitation. The relay is used for a dual purpose, to apply field during starting and to remove field upon pull-out. As the relay characteristic has to be different for the two purposes, contacts on the field application device switch external resistors in series with coils *A* and *B*. Before field is applied, resistor *E* is short-circuited, and resistor *F* and capacitor *H* are in the circuit.

Consider first relay performance during starting. The phase relation between current and potential, together with the magnitudes of current and potential, determine whether field-applying relay contact *a* is open or closed. The current carried by potential coils *A* and *B* is proportional to line voltage, and capacitor *G* in series with coils *B* causes the current flowing in coils *A* and *B* to be out of phase. Thus torque is produced by the interaction between *A* and *B* coils. Current coils *C* carry a current proportional to the current drawn by the motor from the line. The torque resulting from the interaction between *A* and *C* coils depends on the phase angle of the motor current. Thus the resultant torque acting on the movable element of the relay is a function of the impedance of the motor to which it is connected.

A slip cycle on the motor represents two pole pitches, and twice during each slip cycle the reluctance of the magnetic circuit between motor stator and rotor changes at any point due to the passage of a pair of salient poles. As synchronous speed is approached (slip frequency decreasing), the resultant torque acting on the relay shaft undergoes a succession of reversals, the frequency of which depends on the slip of the rotor. These reversals alternately open and close relay contact *a*. As acceleration continues, contact *a* remains closed for longer and longer intervals of time. When this time interval increases to a predetermined value (which can be measured by a timing relay), field excitation is applied at the desired slip frequency. The time interval during which the contact-closing torque predominates over the contact-opening torque can be varied by the adjusting rheostat, which determines the current flowing through *B* coils. Turning the rheostat in the "raise" direction reduces the torque produced by *A* and *B* coils, and as a result field application occurs at a higher speed or at a lower slip. Closing the field circuit when relay contact *a* closes means that field is applied during a time interval during which the motor impedance is high, that is, the flux linkages between rotor and stator poles are high. As explained in Chapter 3, high flux linkages determine a region of favorable angle at which to apply field.

After field excitation has been applied and the motor operates in synchronism, contacts on the field application device recalibrate the relay. Resistor *F* and capacitor *H* are short-circuited, thus increasing the current through *A* coils. Resistor *E* is inserted in series with *B* coils. As long as the motor stays in synchronism, the resultant relay torque keeps contact *a* closed. When the motor pulls out of step, the impedance of the motor stator circuit changes abruptly and the resultant torque acting on the relay contacts reverses, causing contact *a* to open and field excitation to be removed.

Figure 309 is a complete elementary diagram of a synchronous motor starter using a slip cycle impedance relay for field application. Pressing the start push button energizes control relay *CR* and line contactor *M*. While the motor accelerates as an induction motor, the contacts of field relay *FR* alternately open and close once each slip cycle. In conjunction with relay *FR* there is used a timing relay *TR*, which is of the magnetic time drop-out type, as shown in Fig. 108. As long as contact *a* of relay *FR* is closed, a rectified half-wave d-c current flows through *TR* coil and capacitor 1*C* in parallel and in series with resistor 2*R*. Thus a charge is built up on the capacitor, and flux is built up in the magnet of relay *TR*. When contact *a* of *FR* opens and contact *b* closes, the capacitor discharges through resistor 1*R*, and both the capacitor charge and the flux of relay *TR* decay. The amount of build-up and decay represents a measure of the time during which *FR* relay contacts are open and closed or, in other words, a measure of the slip frequency.

When contact *a* of *FR* remains closed for a sufficient period of time so that the voltage across 1*C* and the flux of *TR* build up to a sufficiently high value to cause *TR* to close, the discharge path for capacitor 1*C* through 1*R* is interrupted, and *TR*, being fed current from 1*C*, stays closed during the next partial slip cycle while contact *a* is open. Then, when *FR* contact *a* closes the next time, field contactor *F* is energized, and field is applied. An interlock on *F* opens the rectifier circuit to *TR* coil, but that relay drops out with a time delay and thus maintains a sealing circuit for *F* until any synchronizing current transient, which would cause *FR* contact *a* to open, has disappeared. Another interlock on *F* drops out relay *CR*, which recalibrates relay *FR* so that the circuit is prepared for removing field in case of a pull-out.

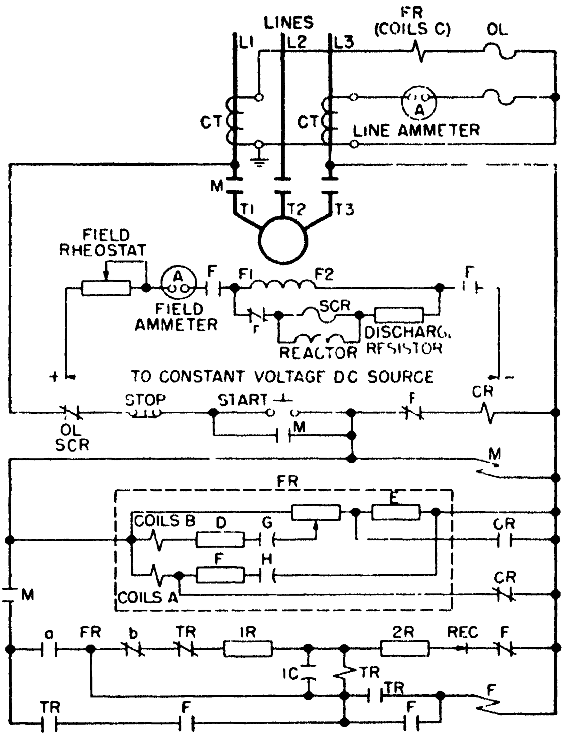


FIG. 309. Synchronous motor starter with slip cycle impedance relay for field application. *M*. Line contactor. *F*. Field contactor. *FR*. Field relay. *OL/SCR* Overload and squirrel cage protective relay. *TR*. Definite time relay. *CR*. Control relay.

If a pull-out occurs, contact *a* on *FR* opens, *F* drops out, and *CR* picks up. The synchronizing control sequence is repeated as described

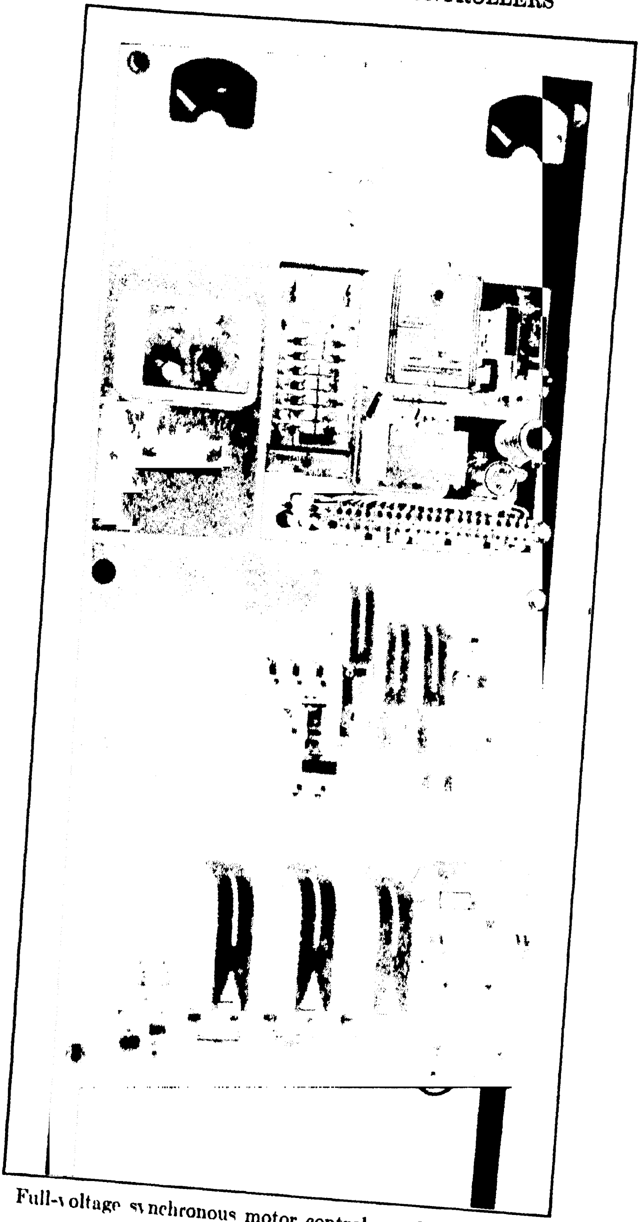


FIG 310 Full-voltage synchronous motor control panel with slip cycle impedance relay

above, and the motor resynchronizes when the load drops sufficiently to permit reacceleration to minimum slip. During operation out of synchronism, the squirrel cage is protected by relay *SCR*, which is a third pole on thermal overload relay *OL*. If the field excitation is supplied by an individual exciter, driven by the synchronous motor, extra contacts on *CR* can be used to short-circuit the exciter field rheostat, which boosts the exciter voltage during synchronization. On standard line starters it is customary to arrange the control circuits in such a way that, by shifting jumpers on the control terminal board, a choice is had between automatic resynchronizing or shutdown in case of a pull-out. If the latter alternative is chosen, the motor is restarted from rest by pressing the start push button.

An open type full-voltage starter for a low-voltage synchronous motor is shown in Fig. 310. The top base contains line ammeter, field ammeter, field rheostat, overload relay, and a field application unit, the cover of which is removed. This unit comprises (from left to right) relays *CR*, *FR*, and *TR*, together with rectifier, capacitor, and resistors. It is a standardized subassembly which can be used on any type of low-voltage or high-voltage starter, no matter what special details the stator control may involve and what size field contactor may be required. On the lower base are mounted the field and line contactors, the size of which is governed by the motor rating.

Special synchronous motor applications may require plugging or dynamic braking to bring the motor to a quick stop. Necessary contactors for reversing the armature or for connecting it to a dynamic braking resistor are then added to the controller. The field application control, however, is not affected, except that field excitation is removed when the motor is plugged.

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CHAPTER 18

DIRECT-CURRENT INTERMITTENT-DUTY CONTROLLERS

On intermittent-duty drives the motors are not called upon to deliver their rated load continuously. They are started and stopped frequently. Motors for such service are applied according to their 15-minute, 30-minute, or 60-minute rating, depending on the severity of the service. Maximum torque and maximum starting torque which the motor is able to deliver and the ability to withstand high current peaks, rather than heating under continuous load, are the basis on which motors are selected. Fast acceleration is an important requirement; thus high torque available for a high rate of acceleration makes series motors the preferred type for intermittent drives. For some applications compound motors are preferred, but shunt motors are seldom used. Therefore, controllers for series motors form the major subject of this chapter.

The most important categories of intermittent-duty drives are steel mill auxiliaries, cranes, and hoists. Controllers are manually operated by pilot devices, mostly master switches. The operator must be able to start and stop the motor and to vary its rate of acceleration and deceleration and its steady state speed at will. A complete controller consists of magnetic control panel, resistor, master switch, and limit switches, if required.

TABLE 26

CONTACTOR RATING FOR 230-VOLT D-C INTERMITTENT-DUTY CONTROLLERS

8-Hour Contactor Rating in Amperes	*Mill or Crane Rating in Amperes*	*Mill or Crane Rating in Horsepower*	*Minimum Number of Accelerating Contactors* *	
			Mill	*Crane*
100	133	35	2	3
150	200	55	2	3
300	400	110	2	3
600	800	225	2 or 3 †	4
900	1200	330	3	4
1350	1800	500	3	4

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* Exclusive of plugging contactor.

† As specified by user.

NEMA has standardized the motor sizes with which various contactors are to be used (see Table 26). The mill or crane rating of contactors is one third higher than their standard 8-hour rating. No contactors having an 8-hour rating of less than 100 ampere shall be used. Accelerating contactors are of the same size as line contactors and are equipped with blowouts, if they may be opened and closed under load at the will of the operator. The minimum number of accelerating contactors which may be used is specified by NEMA standards. On reversing plugging controllers, the plugging contactor is in addition to the accelerating contactors listed in the table

Steel Mill Auxiliaries

NEMA defines steel mill auxiliaries as machines used directly in the processing of steel, such as screwdowns and manipulators, but not cranes and main rolling drives. Standard mill auxiliary controllers include, in addition to devices required to obtain a specific motor performance:

Double pole main line knife switch with lockout device.
Double-pole fused control circuit switch.
Two automatic reset overload relays.
Undervoltage relay.
Negative line contactor.

No standard has been established concerning the type of overload relays used for intermittent-duty controllers. Protection is required against excessive torque and current peaks and against short circuits. Some users prefer instantaneous overload relays; others prefer inverse time or combination inverse time and instantaneous relays.

In place of fused control circuit switches, some users substitute small air circuit breakers to protect the control circuits.

Many steel mill auxiliaries are equipped with adjustable-voltage control, and the amplidyne has found many applications in this field. See Chapter 13 for amplidyne control circuits.

Cab-Operated Cranes [1]

Two basic types of controllers are used on cranes. One type is used for propelling motions of trolleys and bridges on traveling cranes, or the slewing motion on rotating cranes. For these drives the controller is required to start and accelerate the motor in both directions of travel, and to control the rate of acceleration and the speed of travel. During deceleration preparatory to stopping, the kinetic energy of the moving masses must be absorbed. Mechanical braking and friction are not sufficient to obtain quick and smooth stopping, and a good travel motion controller must provide means to absorb electrically the kinetic energy which tends to overhaul the motor.

The second type of controllers pertains to hoists. During hoisting, the motor must be started, accelerated, and stopped while delivering power to the load. During lowering, the load overhauls the motor under the influence of gravity, and the motor must deliver a torque opposing the load torque. However, with an empty hook, a driving torque is needed to lower the hook. Occasionally, on small cranes, a mechanical load brake is used which absorbs the kinetic energy of the overhauling load by friction. The great majority of crane hoist controllers utilizes some form of dynamic braking circuit, dissipating the kinetic energy of the load in resistors, or pumping it back into the line.

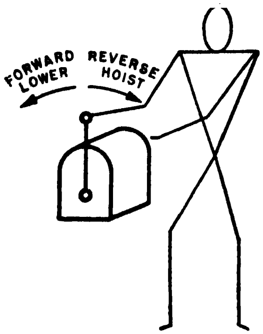


Fig. 311. Standard throw of crane master switches.

NEMA has established certain recommended practices adhered to by manufacturers offering standard crane controllers. They apply to all motions generally.

1. A double pole line switch with lock-out is provided on each control panel, or on a protective panel. This switch has a continuous rating of not less than the 8-hour rating of the contactors used.
2. Undervoltage and overload protection must be provided, either on the individual control panel or on a protective panel.
3. Terminal lugs for outgoing power cables are selected to accommodate a cable having a carrying capacity of 125 per cent of the 8-hour rating of the contactors or switches used.
4. Bridge and trolley controllers include at least three hand-controlled speed points, and hoist controllers at least five hand-controlled speed points in each direction of operation.

Direction of master switch throw is also standardized. Pushing the handle away from the operator obtains lowering or forward travel. Pulling the handle toward the operator obtains hoisting or reverse travel, as shown in Fig. 311. Standard master switch rotation is such that, viewing the master switch from the handle end, counterclockwise handle rotation obtains lowering or forward travel, clockwise handle rotation obtains hoisting or reverse travel. When designing a controller, it is important to observe correct master switch handle throw when the contact closing sequence is not symmetrical in both directions, which is true of all dynamic braking hoist controllers. Conditions at individual installations may require a deviation from the standard switch rotation. Such conditions should be specifically stated by purchasers of crane controllers as manufacturers, unless instructed otherwise, supply master switches with standard handle throw.

Crane Protective Panels

On many cranes, especially traveling shop cranes, there is not sufficient room in the crane cab to accommodate the control panels, which are then mounted overhead on the bridge girder. Thus the panels are not within easy reach of the operator, and he has to climb stairs or a ladder to open line switches on the control panels. In such cases it is customary to omit line switches and protective relays from the individual control panels and to install in the cab a wall-mounted protective panel, providing means to disconnect power from all motors, and overload and undervoltage protection.

The equipment, recommended by NEMA for d-c crane protective panels, is:

One double-pole knife switch with lockout.
Two single-pole contactors to open both sides of the line.
One set of self-reset overload relays, one coil for each motor in the positive side, and one coil in the common negative line to all motors.
Two pilot light receptacles and fuses.
Two control circuit fuses.

TABLE 27

Standard Contactor Ratings for D-C Crane Protective Panels

Standard 8-Hour Rating in Amperes	*Total Horsepower All Motors at 230 Volts*	*Greatest Horsepower Required by Any Single Crane Motion*
100	55	35
150	80	55
300	160	110
600	320	225
900	480	330
1350	725	500

One momentary contact reset-stop push button station, mounted separately from the panel.

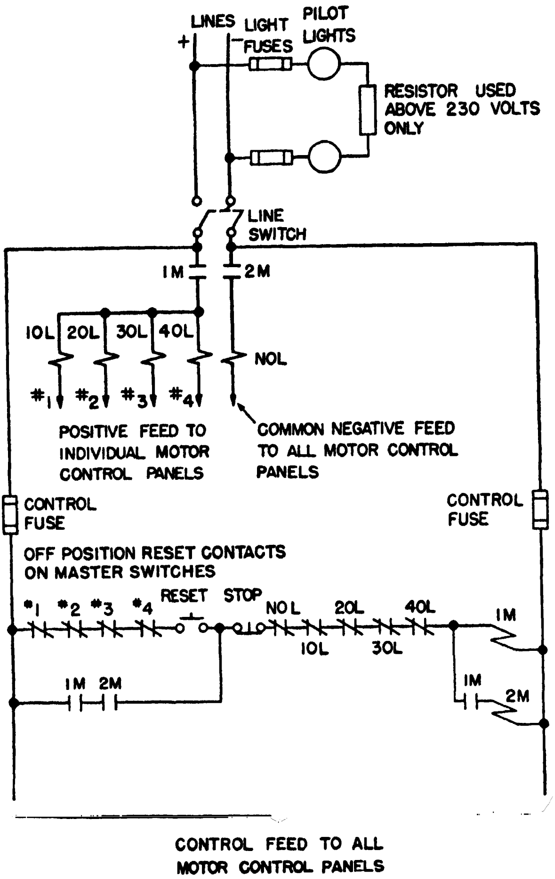

LINES
+
−
LIGHT FUSES
PILOT LIGHTS
RESISTOR USED ABOVE 230 VOLTS ONLY
LINE SWITCH
1M
2M
1OL
2OL
3OL
4OL
NOL
#1
#2
#3
#4
POSITIVE FEED TO INDIVIDUAL MOTOR CONTROL PANELS
COMMON NEGATIVE FEED TO ALL MOTOR CONTROL PANELS
CONTROL FUSE
CONTROL FUSE
OFF POSITION RESET CONTACTS ON MASTER SWITCHES
#1 #2 #3 #4
RESET
STOP
NOL
2OL
4OL
1OL
3OL
1M
1M 2M
1M
2M
CONTROL FEED TO ALL MOTOR CONTROL PANELS

Fig. 312. Connections of d-c crane protective panel. 1*M*, 2*M*. Line contactors. 1*OL*, 2*OL*, 3*OL*, 4*OL*. Positive line overload relays. *NOL*. Negative line overload relay.

The size of line contactors used on protective panels is governed by the following considerations:

1. The 8-hour rating shall be not less than 50 per cent of the combined intermittent current rating of all motors, or less than 75 per cent of the sum of the intermittent-current ratings of the motors required for any single crane motion.

2. In no case shall the line contactors of the protective panel be of a smaller rating than the largest contactor used on any of the controllers protected thereby.

The continuous rating of the line switch is not less than the 8-hour rating of the line contactors. Standard contactor ratings for 230-volt applications are listed in Table 27.

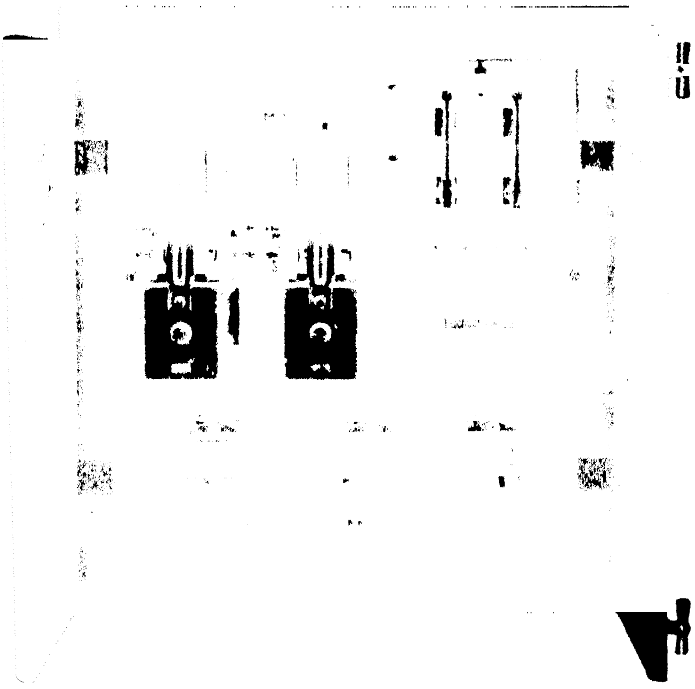


FIG. 313. D-c crane protective panel with front cover.

Shown in Fig. 312 is the elementary diagram of a typical protective panel for four motors. Two pilot lights are connected across the incoming line to indicate that power is available. On 230-volt panels, two standard 115-volt lamps are used in series. On higher voltages, a resistor is connected in series with the lamps. Off position reset contacts of the master switches are connected in series with the reset push button. Before the line contactors can be closed, all master switches must be turned to the neutral position, thus opening the power circuits to the individual motors. The line con-

tactors are sequenced, 1*M* closing first and then 2*M*. Thus 1*M* does not close under power, which minimizes the danger of both line contactors welding closed in case a short circuit exists on the system. Control lines are connected to the individual control panels ahead of the line contactors so that the control sequence of each control panel can be tested with the power circuit open.

Protective panels may be either open or enclosed. Overload relays may be instantaneous or inverse time. Figure 313 is a view of a typical four-motor protective panel with enclosing cover over the front, guarding the operator against accidental contact with live parts. The line switch can be operated from the outside. A bull's-eye in one front door serves to observe the pilot lights. The instantaneous overload relays are of the double-coil type, two relays protecting the four positive motor lines and a third relay with one dummy coil protecting the common negative line.

Bridge and Trolley Controllers [2]

Bridge and trolley controllers are of the reversing type, usually with plugging protection for quick stopping and rapid reversing. Series brakes are sometimes used which release on a motor current of 40 per cent of normal. As the inductance of series brake coils is low, the brakes release and set promptly whenever the motors are energized or de-energized, permitting accurate jogging or spotting. On very large trolleys, for instance, of ore and coal bridges, shunt wound brakes must be used for two reasons. First, with the large motor sizes which are often encountered, brake sizes exceed the largest type of series brakes available. Second, motor sizes are determined by torque and rate of acceleration, and power consumed during free running on these applications may be so low that series brakes are liable to set. Some trolleys are equipped with parking brakes only which are set when the crane is shut down and are held released while the crane is in operation.

NEMA Standards prescribe the minimum equipment which a single-motor trolley or bridge control panel should contain:

One double-pole line switch with provision for locking in the open position.
One double-pole control switch and fuses.
Two automatically reset overload relays, one for each side of the line.
One undervoltage relay.
One negative line contactor.

One set of reversing contactors, containing a total of four normally open poles, mechanically interlocked.

One plugging contactor with means to prevent automatically closing of the contactor unless the motor speed is approximately zero.

One set of accelerating contactors, the number of which is governed by Table 26, with automatic timing means for each contactor.

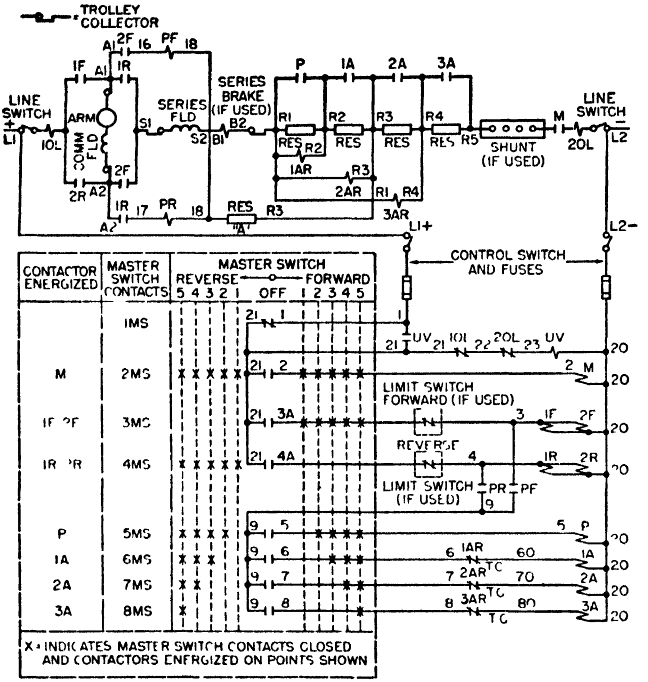
If the panel is used in conjunction with a protective panel, the line switch, the overload relays, and the undervoltage relay are omitted

Figure 314 is an elementary diagram of a reversing, plugging controller with five manually controlled speed points, obtained by a five-position master switch. The principal control circuits are the same as described previously in Chapter 11, and reference is had to Fig. 240 and the accompanying detailed description of contactor sequence. Included in Fig. 314 is a contactor sequence table, indicating by *x* marks the contactors which are closed on the various master switch positions. Also included is a relay setting table, giving relay adjustments which experience has shown to be correct for average applications. Further adjustment may be required in special cases.

The controller provides the following operating features:

1. In case of overload or loss of voltage, all contactors drop out and the brake sets.
2. When the overload relays reset or voltage reappears, the master switch must be returned to the off position, resetting relay *UV*, before the motor can be started again.
3. Acceleration is controlled by definite time drop-out accelerating relays which control accelerating contactor closing in definite time sequence.
4. During plugging, contactor *P* is held open, until the motor has decelerated practically to zero speed, by plugging relays *PF* and *PR*. Resistor *A* in series with the plugging relay coils reduces the effect of variations in line voltage on the motor speed at which the relays close.

Trolley control panels are usually mounted on the bridge, and trolley wires are required between the control panel and the motor. The diagram indicates the circuits which have to be carried through trolley wires if the motor and the panel are mounted on parts of the crane which move relative to each other. If limit switches are used to stop movement automatically at the ends of travel, the limit switch contacts are wired so that they drop out the directional and accelerating contactors. Backing out of the limit is possible by turning the master switch in the opposite direction. To facilitate testing of



CONTACTOR SEQUENCE TABLE											
MASTER HANDLE POSITION	REVERSE					OFF	FORWARD				
	5	4	3	2	1		1	2	3	4	5
CONTACTORS M	X	X	X	X	X		X	X	X	X	X
1F 2F							X	X	X	X	X
1R 2R	X	X	X	X	X						
P	X	X	X	X				X	X	X	X
1A	X	X	X						X	X	X
2A	X	X								X	X
3A	X										X

X = INDICATES CONTACTORS CLOSED

CONTACTOR NOMENCLATURE		
1F	FORWARD	1F 1R 2F 2R MECHANICALLY INTERLOCKED
2F		
1R	REVERSE	
2R		
P	PLUGGING	
1A	ACCELERATING	
2A		
3A		
M	NEGATIVE LINE	

RELAYS				
NOMENCLATURE		GAP	SETTING	
1AR	ACCELERATING	1/8	0.75	SEC TO RELEASE
2AR		1/8	1.25	
3AR		1/8	1.00	
PF	PLUGGING	5/16	55	% VOLTS PICK UP
PR		5/16	55	
UV	UNDERVOLTAGE	3/8	65	
1OL 2OL	OVERLOAD	250% FULL LOAD AMPS		

FIG. 314. Elementary diagram of reversing plugging crane bridge or trolley controller.

motor current consumption at the installation, a shunt in the motor power circuit may be included as an optional item.

Speed-torque curves obtained with a controller as described are plotted in Fig. 315. Performance curves obtained on forward master switch positions are designed by letter *F* and those obtained on reverse master switch positions by letter *R*. Two curves are shown for the first master switch position, one for sleeve-bearing cranes and one for roller-bearing cranes. The difference between the two curves is due to a different amount of resistance provided in the plugging resistor section $R1$–$R2$. For sleeve-bearing cranes the resistor is designed so that the starting torque on the first master switch position is approximately one half of motor full-load torque. Because of the friction in the bearings, the free running motor speed does not rise materially above full-load speed, and the initial plugging torque is between 1.0 and 1.25 motor full-load torque. When cranes are equipped with roller bearings, friction is considerably lower, and the free-running speed may rise to approximately 1.6 of normal speed. The resistor lay-out as used for sleeve-bearing cranes would then result in too high a plugging torque, and additional resistance is used in resistor section $R1$–$R2$, which reduces the starting torque on the first master switch position to less than 0.4. With such a resistor lay-out, the plugging torque at a speed of 1.6 is reduced to approximately full-load torque.

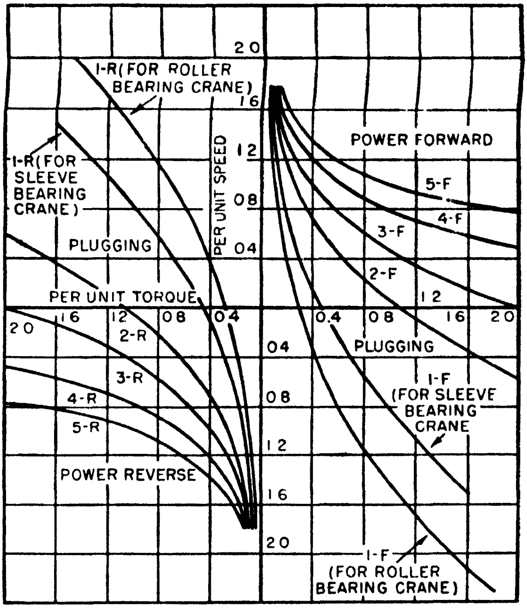


Fig. 315. Speed-torque curves of a reversing plugging crane travel controller.

As far as thermal capacity is concerned, resistors for standard-duty cranes, for instance, general-purpose shop cranes, are designed to meet NEMA class 152. For heavy-duty cranes, such as frequently operated steel mill cranes, resistor classification 162 is used. Occasionally, for extra heavy duty, as may be encountered on busy ore bridges or other cranes handling bulk material, NEMA class 172 resistors may be warranted.

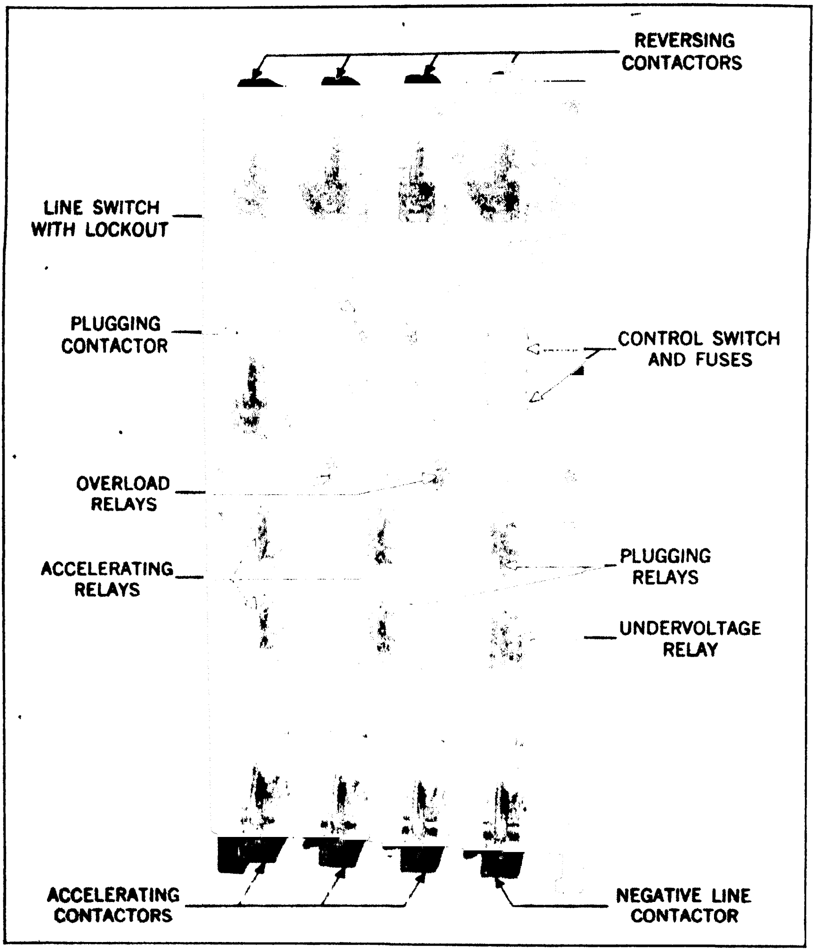


FIG. 316. Typical open type crane travel control panel.

Figure 316 is a view of a typical open type crane travel control panel. Contactors are arranged at the top and bottom, with ample space above the arc chutes. Switches and relays are arranged between the contactors at a height where they can be reached conveniently by an operator.

Duplex Bridge Controllers[3]

One or several pairs of motors are often used for the bridge motion of heavy cranes. Typical examples are gantry or bridge cranes on which motors are paired on the trucks driving the legs. Pairs of motors are sometimes used to drive the heavy man trolleys of ore bridges. In such cases it is necessary to control all motors comprising a drive as a unit, so that the motors accelerate and decelerate in unison. The question naturally arises as to what method of connecting two motors in a duplex controller will obtain satisfactory performance under all service conditions. In Chapter 2 it is explained that series motors with correctly designed control lend themselves naturally to parallel operation when connected to a common mechanical load. No particular problems arise as long as both motors deliver power to the load. However, when motors are driven by the load during plugging, difficulties may be encountered and the details of the duplex power circuit are of importance.

Shown in Fig. 317 are several possible arrangements of power circuits for two series motors. In sketch *A* the armatures of two motors *A* and *B* are connected in series, and so are their fields. With this connection, the pair of motors is treated just as if it were one motor, and the same current flows through both armatures and both series fields, during acceleration as well as during plugging. This connection is widely used on gantry cranes in shipyards, where as many as four or eight motors, arranged in pairs, may drive the trucks. With a power system of 250 volts, motors are used which are rated 125 volts. If motors rated 250 volts were used, they would be operated at half their rated speed or at half their rated power output. In plants which use many d-c motors at 250 volts, as in steel mills, this duplex connection is not considered desirable, as the 125-volt motors would require spare parts different from the spare parts for the rest of motors in the plant. From an engineering point of view, this control system is entirely satisfactory, but considerations of plant management may decide against it.

In sketch *B* the motor armatures are connected in parallel and the fields in series. Thereby 250-volt motors on a 250-volt line can be operated at full output. The same current flows through the series fields of both motors, and operation is satisfactory during acceleration and during plugging. Slight differences in armature resistance may cause different current to flow in the two armatures, but this does not prevent proper operation during plugging, as any change in torque causes the current in both fields to change by an equal amount. Caution must be exercised in applying this circuit as the fields carry twice armature current, and, if standard motors are used on a heavy-duty drive, the motor fields are likely to overheat.

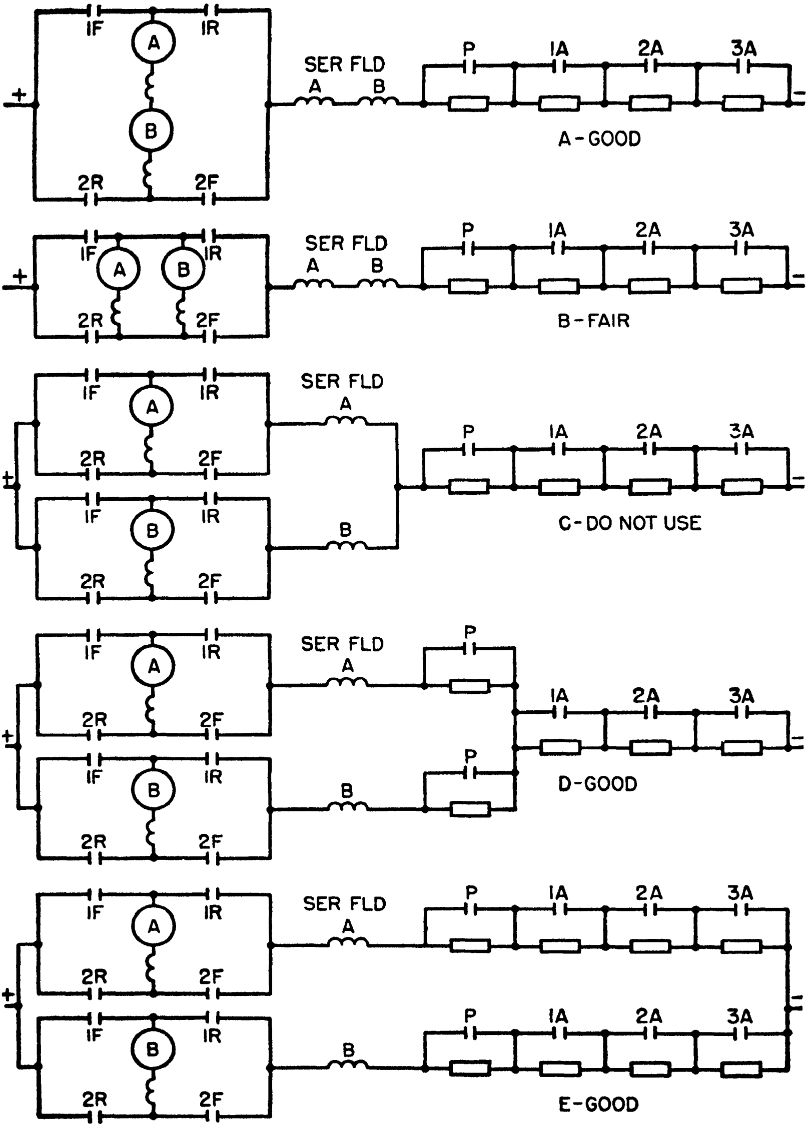


FIG. 317. Possible power circuits for duplex crane bridge controllers.

This danger is avoided by the connection of sketch *C*, in which each motor armature and its field is connected in parallel with the other motor armature and field. A common resistor with common plugging and accelerating contactors is used for the pair of motors. This connection is satisfactory for acceleration, but very poor performance is obtained during plugging. A slight difference in internal resistance always exists between the two motors. During plugging, the motor with the lower resistance draws more current, its field becomes stronger, its counter emf becomes greater, it draws still more current, and so forth. As a result high circulating current will flow through the two motor armatures, and one motor will drive the load, whereas the other motor will retard the load, both motors working against each other. Connection *C* must not be used for drives which are plugged.

Connecting a plugging section of the resistor in series with each motor field overcomes this difficulty, as illustrated by sketch *D*. The slight difference in internal motor resistance becomes an insignificant portion of the total resistance in each parallel motor path, and circulating current between the two motors is suppressed effectively. Only one set of accelerating contactors is used, but they must be of twice the size of the reversing and plugging contactors. Thus two sizes of contactors are used on the same controller, which is objectionable since two sets of spare parts must be stocked.

A preferred power circuit is indicated in sketch *E*. Each motor armature and field circuit is kept entirely separate, each motor having its own resistor and its own set of contactors. As both sides of each parallel path are anchored to line potential, the currents flowing through the two motors are substantially equal, and both motors divide the load evenly during accelerating as well as during plugging. All contactors are of the same size so that only one set of spare parts needs to be provided.

Another advantage of this connection is that, in case of motor failure, one motor can be disconnected and emergency operation can proceed with one motor at reduced speed. Figure 318 shows the complete power circuit of a practical duplex controller of the type shown in Fig. 317*E*. An individual line switch in each motor circuit permits isolating either motor. Control connections and contactor closing sequence are the same as shown in Fig. 314 except that two sets of contactors operate on each master switch position. In order to close corresponding contactors of both motor circuits simultaneously, one set of accelerating and plugging relays is used. A relay transfer switch is included, with which the relay coil circuits can be connected to the power circuit of either motor. During normal operation, it is immaterial to which motor the relays are connected. During emergency operation, however, the transfer switch must be closed in the proper direction to connect the relays to the power circuit of the motor which stays in service.

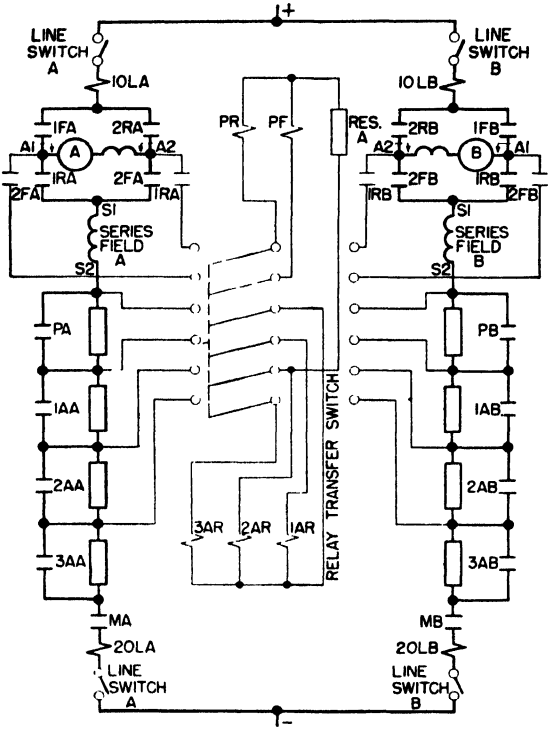
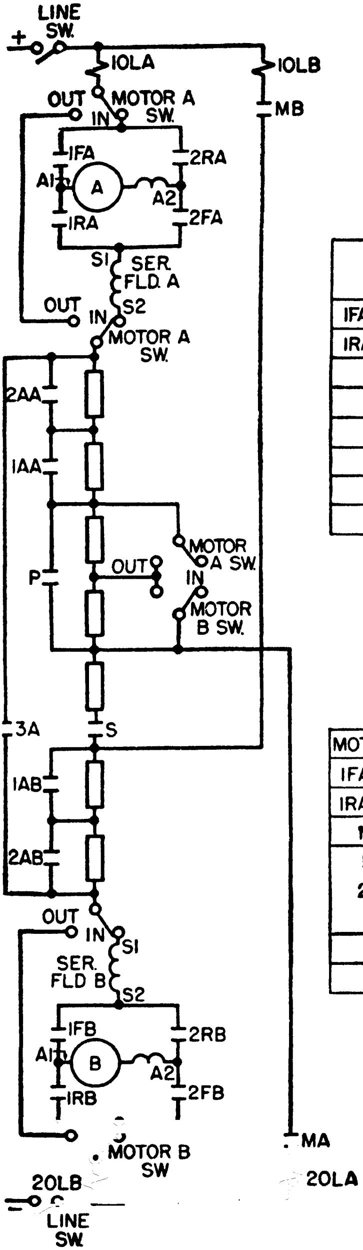


FIG. 318. Complete power circuit of a duplex plugging crane bridge controller Device nomenclature and contactor closing sequence same as in Fig. 314.

Series-Parallel Controllers

Two series motors may be accelerated by connecting them first in series and then in parallel. With the series connection they are accelerated to half their normal speed, and with the parallel connection to full speed. This method of control is used when operation at half speed or below is frequent, since the series connection obtains more stable speed-torque curves in the lower speed range, and acceleration is smooth, when heavy masses are to be moved. Series-parallel control is most often used for heavy trolleys and for the slewing motion of large shipyard cranes.



CONTACTOR CLOSING SEQUENCE

	REVERSE					OFF	FORWARD				
	5	4	3	2	1		1	2	3	4	5
1FA,2FA,1FB,2FB							X	X	X	X	X
1RA,2RA,1RB,2RB	X	X	X	X	X						
P	X	X	X	X	X		X	X	X	X	X
1AA,1AB	X	X	X	X				X	X	X	X
2AA,2AB	X	X	X						X	X	X
3A		X								X	
S			X	X	X	X	X	X	X		
MA,MB	X										X

CONTACTOR NOMENCLATURE

MOTOR A	MOTOR B	
1FA,2FA	1FB,2FB	FORWARD
1RA,2RA	1RB,2RB	REVERSE
MA	MB	LINE,PARALLEL
1AA	1AB	FIRST
2AA	2AB	SECOND ACCELERATING
3A		THIRD
P		PLUGGING
S		SERIES CONNECTION

FIG. 319. Power circuits of series-parallel reversing plugging controller.

Figure 319 is an elementary diagram of the power circuit of a typical series-parallel controller, and a contactor sequence table indicates which contactors are closed on the various master switch positions. Plugging is possible, and plugging relays are connected across the armature circuit of one motor. During plugging the motors are connected in series, same as on master switch position 1,

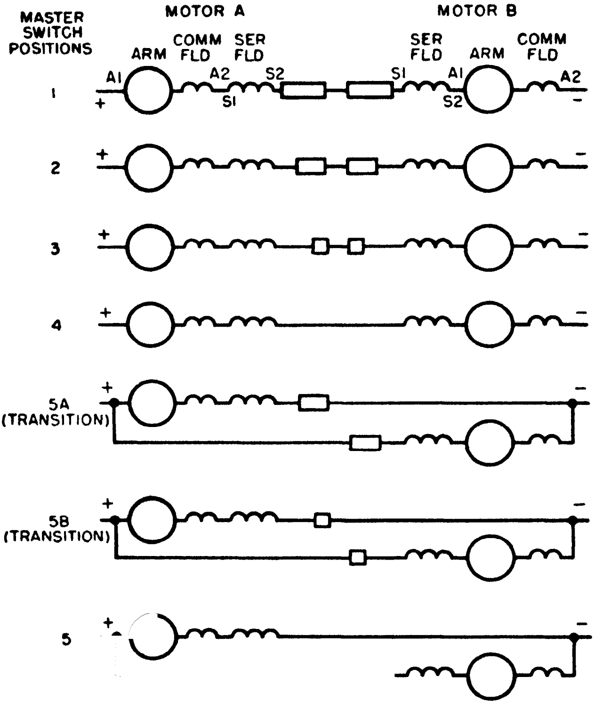


Fig. 320. Step-by-step power circuit diagram of series-parallel controller.

except that plugging contactor *P* remains open, and an additional block of resistance is connected in series with the motors to reduce the plugging torque to a desirable value.

For emergency operation with one motor a double-throw cut-out switch is provided for each motor. With both motors in service the switches are closed in the "in" position as shown. When either motor is taken out of service, its switch is thrown in the "out" position. This closes a by-pass circuit around the armature of the faulty motor, and the remaining motor functions as a single motor with straight reversing, plugging control with full voltage applied to that motor. During single-motor operation, one half of the plugging resistor section is short-circuited so that the plugging torque of one motor becomes nearly as great as the plugging torque of the two motors.

As a help in understanding the sequence of operation, the principal connections of the motor power circuit on the various master switch positions are shown in Fig. 320. On the first step, both motors are in series, with all accelerating resistance in the circuit. On steps 2 to 4 accelerating resistance is cut out by the closing of accelerating contactors. On master switch position 4, the motors are across the line, each absorbing one half line voltage and thus operating at one half speed. There is no power loss in external resistance, and this method of control is very efficient from the point of view of power consumption, if operation at reduced speed is frequent.

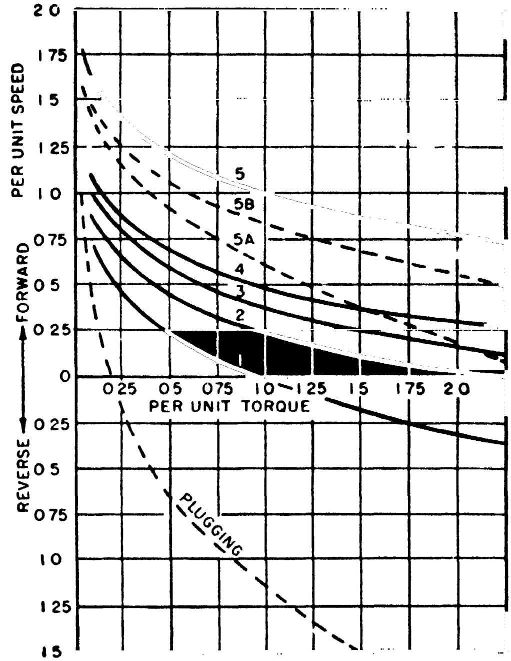


FIG. 321. Speed-torque curves of series-parallel controller.

On the fifth master switch position, the series connection is broken, and line contactors close which connect the two motors in parallel. The transition is rapid so that the motors do not lose speed. To limit the armature current to a safe value, resistance is reinserted in series with each armature, and the resistance is cut out automatically in two steps, under the control of definite time accelerating relays. Finally, both motors are connected across the line in parallel, and they operate at full speed.

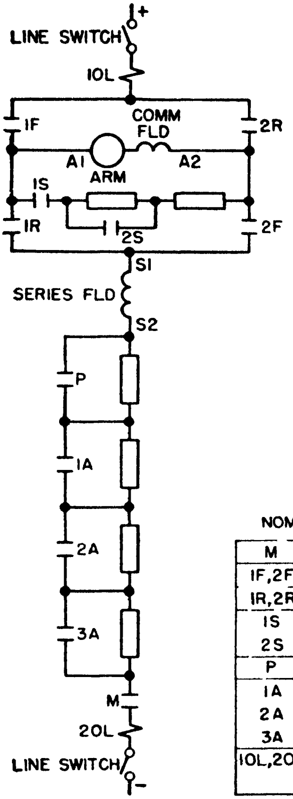
Speed-torque curves, which are obtained with series-parallel control, are plotted in Fig. 321 for a typical installation. Some variations in the curves are possible, to meet special requirements, by making changes in the resistor lay-out. For instance, by varying the amount of resistance connected in the circuit on master switch position 1, a different amount of starting torque may be obtained. The curves are plotted for one direction of rotation only, and the curves for reverse rotation are symmetrical. Torque is expressed in terms of per unit torque of both motors, delivered at the shaft of the driven machine. A comparison with Fig. 315 shows that in the range below half speed the change in speed for a given change in torque is approximately halved.

Armature Shunting

At no load or at light loads, a series motor attains a very high speed, and inserting resistance in series with the motor does not obtain any appreciable reduction in motor speed. On fast crane motions, for instance, man trolleys of ore bridges or slewing motions of revolving cranes, the motor size is often determined largely by the torque required for fast acceleration, and the free running torque may fall well below one quarter of the motor full-load torque. On ore bridge propelling drives, a tail wind may unload the motors, because of the large area of the structure against which the wind may push. To obtain speed reduction on such drives, shunting of the motor armature may be employed, the function of which is explained in Chapter 2.

Figure 322 is an elementary diagram of the power circuit of a reversing controller with two steps of armature shunting. Connections are similar to the ones shown in Fig. 314, except that contactors 1*S* and 2*S*, as well as shunting resistance, are added to the armature circuit. On the first master switch position, contactors 1*S* and 2*S* are closed, and a stiff, low resistance shunt is placed around the armature. On the second master switch position, contactor 2*S* drops out and the shunting resistance is increased. Contactor 1*S* opens on the third master switch position, the shunting connection is removed, and the motor operates with straight series connection. The corresponding speed-torque curves are plotted in Fig. 323. Definite no-load speeds are obtained on master switch positions one and two, and a uniform spread exists between light load speeds on the various master switch positions.

If the drive operates at full speed and the master switch is moved back to position two or one, the inertia of the drive overhauls the motor. A negative braking torque is developed by the motor, which results in rapid slowing down of the drive. Control sequence of contactors should be so interlocked that a definite time delay is provided between the closing of contactors 1S and 2S, so that the braking torque is applied in steps and too severe braking is avoided.



CONTACTOR CLOSING SEQUENCE

	REV			OFF	FOR		
	3	2	1		1	2	3
M	X	X	X		X	X	X
1F, 2F					X	X	X
1R, 2R	X	X	X				
1S		X	X	X	X	X	
2S			X	X	X		
P	X	X	X		X	X	X
1A	X	X				X	X
2A	X						X
3A	X						X

NOMENCLATURE OF DEVICES

M	NEGATIVE LINE CONTACTOR
1F, 2F	FORWARD CONTACTORS
1R, 2R	REVERSE CONTACTORS
1S 2S	FIRST SECOND } ARMATURE SHUNT CONTACTORS
P	PLUGGING CONTACTOR
1A 2A 3A	FIRST SECOND THIRD } ACCELERATING CONTACTORS
1OL, 2OL	OVERLOAD RELAYS

FIG. 322 Power circuits of reversing crane travel controller with armature shunting

Although armature shunting control obtains rapid slow-down by returning the master switch toward the off position, eliminating the necessity for plugging, it is advisable to include provision for plugging in the controller. Plugging of crane drives is such a common performance that any crane operator is likely to plug a motor, even when operation with shunted armature would be the desired method of slowing down. Plugging a motor with its armature shunted would obtain such an excessively high plugging torque that damage to gearing and shafting would be likely to occur. For this reason, a plugging contactor *P* is indicated in Fig. 322. During plugging, armature shunting contactors 1*S* and 2*S* are prevented from closing until after the motor has been retarded to practically zero speed. Plugging relays which control the closing of contactor *P* serve to lock out contactors 1*S* and 2*S*.

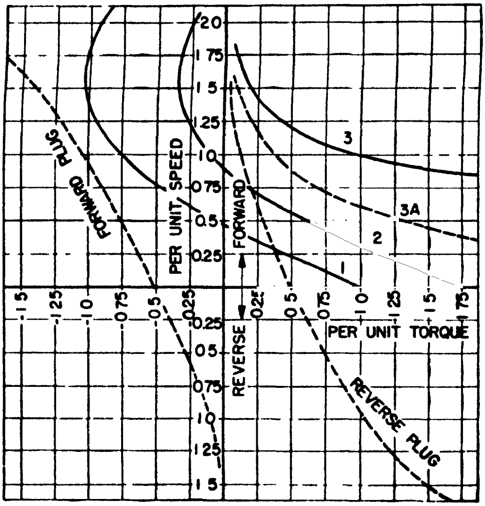


Fig. 323. Speed-torque curves of crane travel controller with armature shunting.

Dynamic Braking [1]

On fast-moving crane travel drives it is desirable not to apply the mechanical brakes immediately upon returning the master switch to the off position, lest severe braking torque be applied at high speed. Setting of the brakes is delayed and motor speed is reduced by an automatic decelerating sequence, making use of the motor's ability to develop a dynamic braking torque. A similar condition arises in case of failure of the power supply and emergency dynamic braking may be desired in case of loss of power.

As has been explained in Chapter 2, dynamic braking can be obtained by connecting the armature, the series field, and a resistor in a series loop circuit, with no connection to the line. The motor then acts as a series generator, and the kinetic energy of the moving masses is dissipated in the dynamic braking resistor. In laying out a dynamic braking circuit, care must be taken that the emf of the motor armature causes current to circulate through the series field in the same direction in which current flowed before the dynamic braking loop was closed, as otherwise the dynamic current would reduce the series field flux to zero and prevent self-excitation. Although it is easy to provide for dynamic braking on a non-reversing controller, certain precautions must be taken with reversing controllers, as the direction of armature emf is different in both directions of rotation. Several contactors are necessary to obtain a workable dynamic braking connection.

If dynamic braking is desired primarily as a decelerating sequence upon return of the master switch to the off position, normally open contactors, requiring power to close them, may be used. If the emphasis, however, is placed on obtaining emergency dynamic braking in case of power failure, the control system must be based on the use of normally closed contactors, which are spring-closed when power is removed from their coils so that they will close their contacts when the power supply fails.

Shown in Fig. 324 are two control systems which obtain dynamic braking on reversing controllers. Sketch *A* is the elementary power circuit of a single-motor controller. It contains the same basic circuit elements as given in Fig. 314, but four dynamic braking contactors 1*DB*, 2*DB*, 3*DB*, 4*DB* have been added, together with a block of resistance connecting the series field and armature together. The dynamic braking contactor coils are energized as soon as the master switch is moved out of the off position, and during normal operation their contacts are open. They have no effect on acceleration and plugging performance. When the master switch is turned to the off position, or when power fails, the contactor coils are de-energized. In order to obtain proper direction of current flow through the series field, only two contactors are allowed to close, and the other two are locked open mechanically. 1*DB* and 2*DB* operate together, and so do 3*DB* and 4*DB*. The mechanical lockout consists of a cam shaft, whih is turned one way or the other by a pair of solenoids, depending on the direction in which the master switch had been turned.

When the motor operates in the forward direction, the cam shaft is turned so that contactors 1*DB* and 2*DB* are free to close, but 3*DB* and 4*DB* are locked open. While the motor is connected to the line, current flows through the armature from *A*1 to *A*2 and through the field from $S1$ to $S2$. When the master switch is moved to the off position, or when power fails, all normally open contactors drop out and $1DB$ and $2DB$ close. The counter emf of the motor is in such a direction that current flows through the armature from $A2$ to

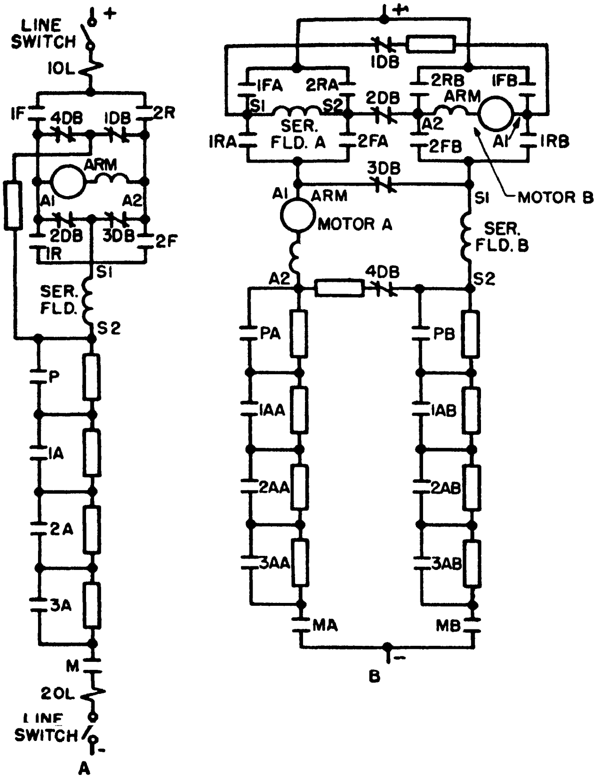


FIG. 324. Emergency dynamic braking connections for reversing crane travel controllers. *A*. Single-motor system with mechanically locked contactors. *B*. Wilson-Ritchie system for two-motor drives.

$A1$, through $2DB$ and the series field from $S1$ to $S2$, through resistor and $1DB$ back to $A2$. Thus current through the series field is in the same direction as before the dynamic braking loop was established, and self-excitation takes place.

In case the master switch is turned to reverse, the cam shaft is turned so that contactors $1DB$ and $2DB$ are locked open, whereas $3DB$ and $4DB$ are free to close. Current then flows through the motor armature from $A2$ to $A1$, and through the field from $S1$ to $S2$. Moving the master switch to the off position or a power failure causes contactors 3*DB* and 4*DB* to close. The motor counter emf causes current to flow through the armature from *A*1 to *A*2, through 3*DB* and the series field from *S*1 to *S*2, and back through the resistor and 4*DB* to *A*1. Current flow through the series field is correct, and dynamic braking torque is developed by the motor.

The mechanical lock-out feature necessary to obtain proper operation of the dynamic braking contactors prevents the use of standard spring-closed contactors. In order to avoid this complication, a dynamic braking system has been developed for duplex drives, shown in sketch *B*. Named after its inventors, it is generally known as the Wilson-Ritchie system. The power circuit is similar to the one shown in Fig. 318. However, armature and field of motor *A* are interchanged, and the series field is reversed instead of the armature. Dynamic braking contactors 1*DB*, 2*DB*, 3*DB*, 4*DB* are standard spring-closed contactors which open their contacts when the master switch is moved out of the off position and close when the master switch is returned to neutral or when power fails.

During forward operation current flow through motor *A* is in the direction *S*1–*S*2–*A*1–*A*2. Current flow through motor *B* is in the direction *A*1–*A*2–*S*1–*S*2. When the dynamic braking contactors close, the armature of motor *B* is connected to the field of motor *A* so that current flows in the direction *A*2–*A*1–*S*1–*S*2, and the field is excited in the correct sense. The armature of motor *A* is connected to the field of motor *B*, and current flow is in the direction *A*2–*A*1–*S*1–*S*2, which is also correct. If dynamic braking takes place after the motors have operated in the reverse direction, current flow through motor *B* armature and motor *A* field is reversed, whereas in motor *A* armature and motor *B* field it stays the same as for forward operation. Thus correct field excitation is assured, regardless of direction of motor rotation.

By introducing additional contactors, which change the value of resistance in the dynamic braking loops, the dynamic braking torque can be graduated and maintained at a higher average value, while the motors decelerate. The peculiar cross connection between armatures and fields of the two motors prevents dynamic braking action from taking place in case one motor fails and emergency operation is maintained with one motor only.

Crane Hoist Controllers [1, 5]

The peculiar operating condition which governs the design of hoist controllers is that the load is under the pull of gravity. To hoist a load, the motor must overcome gravity and deliver power to the load.

When lowering, the load overhauls the motor, and control of the lowering speed is obtained by the motor exerting a retarding torque, thus becoming a generator transforming mechanical into electric energy which is dissipated as heat in a resistor or pumped back in the line. A light hook, however, may not have sufficient pull to overhaul the motor. Therefore, provision must be made to lower light loads with power.

Controllers for general-purpose cranes, handling a variety of loads between a light hook and full rated load, use lowering circuits in which the motor is connected as a shunt generator with various amounts of resistance in series with the armature, the field, or both. The principles of motor performance and methods for calculating speed-torque curves are discussed in Chapter 2. Hoist controllers of various manufacturers differ in details of circuit arrangement and control sequence. However, they all use the same basic dynamic braking circuit, consisting of a parallel connection between armature and series field. Hoisting does not present any peculiar problems, and the motor operates with straight series connection of armature and field.

The minimum equipment to be included in a crane hoist control panel is listed in NEMA Standards as follows:

One double-pole line switch with provision for locking in the open position.
One double-pole control switch and fuses.
Two automatically reset overload relays, one for each side of the line.
One undervoltage relay.
One set of hoisting and lowering contactors, mechanically interlocked, with provision for opening both sides of the line.
One set of accelerating contactors, the number of which is governed by Table 26, and with automatic timing means for at least two steps in the hoisting direction.

If a protective panel is provided, the line switch, overload relays, and undervoltage relay are omitted. All panels must include dynamic braking in the lowering direction, with or without power being available from the line, and in the off position of the master switch.

Elementary connections of a typical crane hoist controller are shown in Fig. 325. To assist in understanding the function of the controller, the power circuits corresponding to each master switch position are indicated in the step-by-step diagram of Fig. 326. The resultant speed-torque curves are plotted in Fig. 327. A typical crane hoist control panel is shown in Fig. 328.

Series brakes are most commonly used. They release only when current flows through the motor power circuit, that is, when the motor develops torque. Thus they will not release if the motor power circuit is interrupted, which safeguards against a possible run-away of the load. If shunt brakes are used, a series relay should be connected in the power circuit in lieu of the series brake coils, the relay preventing the shunt brake coils from being energized unless motor current flows. Either one brake is used, with the brake wheel on the motor shaft, or two brakes are applied, one on the motor shaft and one on the jack shaft.

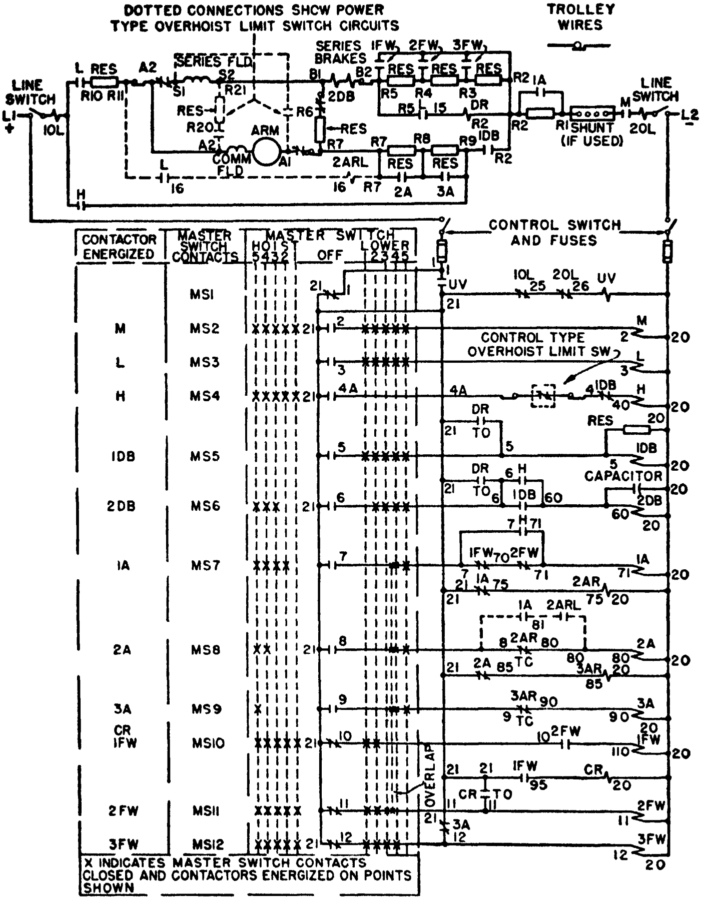
Off Position of Master Switch

With the master switch in the off position, the motor is disconnected from the line, and the brakes are set. An emergency dynamic braking circuit is set up, the armature and series field being connected in a loop circuit through spring-closed contactor *2DB*. When the master switch is moved from a running position to the off position, the dynamic braking circuit assists the mechanical brakes in stopping the load, which reduces brake wear. The same dynamic braking circuit is formed in case of power failure, contactor *2DB* dropping out and closing its contact. Power failure thus results in stopping and holding the load by the combined action of dynamic braking and the mechanical brakes.

Beyond assisting the mechanical brakes, dynamic braking has a greater significance in preventing a dangerous run-away of the load should the mechanical brakes fail to hold the load. Brake failure may be caused by excessive wear, improper adjustment, or mechanical failure of some part. If such a condition arises and the load overhauls the motor without restraint by mechanical brakes, the motor speed is limited by dynamic braking action as indicated by the off position curve of Fig. 327. Dynamic braking cannot stop the load and prevent it from moving, but it does prevent acceleration to excessive speed and causes the load to be lowered at a moderate controlled speed, until the load hits the floor. Such emergency braking is required as a "must" by NEMA Standards.

Hoisting

When the master switch is turned in the hoisting direction, contactors *H* and *M* close (contactors *1FW*, *2FW*, *3FW* staying closed on all positions hoisting) and connect the motor to the line with



CONTACTOR SEQUENCE TABLE											
MASTER HANDLE POSITION	HOIST					OFF	LOWER				
	5	4	3	2	1		1	2	3	4	5
CONTACTOR M	X	X	X	X	X		X	X	X	X	X
L							X	X	X	X	X
H	X	X	X	X	X						
1DB							X	X	X	X	X
2DB				X	X	X	X				
1A	X	X	X	X						X	X
2A	X	X								X	X
3A	X									X	X
1FW	X	X	X	X	X	X	X	X			
2FW	X	X	X	X	X	X	X	X	X		
3FW	X	X	X	X	X	X	X	X	X	X	
X-INDICATES CONTACTORS CLOSED											

CONTACTOR NOMENCLATURE		
M	LINE	
H	HOIST	H L, H-1DB MECH INTERLOCKED
L	LOWER	
1DB		
2DB	DYNAMIC BRAKING	
1A	1ST	ACCELERATING
2A	2ND	
3A	3RD	
1FW	1ST	FIELD WEAKENING
2FW	2ND	
3FW	3RD	

RELAYS				
NOMENCLATURE			SETTING	
UV	UNDERVOLTAGE		PICKUP AT 65%LINE VOLTS	
CR	CONTROL		8	SEC TO RELEASE
DR	DECELERATING		2	
2AR	2ND	ACCEL	5	
3AR	3RD		4	
1OL	OVERLOAD		250	% FULL LOAD MOTOR AMPS
2OL				
2A-RL	CEMF ACCELERATING LOWERING (IF USED)		PICK UP AT 80 % LINE VOLTS	

FIG. 325. Elementary diagram of dynamic braking crane hoist controller.

armature and field in series. Accelerating contactors 1*A*, 2*A*, 3*A* close on successive master switch positions and short-circuit resistor sections in steps. On the first two master switch positions, contactor 2*DB* is left closed and the motor is shunted by resistor section *R*6–*R*7. As was explained in Chapter 2, this connection results in a flattening of the speed-torque curves and in a reduction of light-load speeds, as is evident from Fig. 327. Light loads can be maneuvered more easily, and an empty hook can be jogged more accurately.

Overhoisting protection must be provided to prevent unshackling the hook and dropping the load. Overhoist limit switches are arranged so that the hook block lifts a weight and causes the switch to trip open. If a control type limit switch is used the switch contact is connected in series with the coil of contactor *H*. When the limit switch is tripped, contactor *H* drops out, which in turn causes spring-closed contactor 2*DB* to drop out. The motor is disconnected from the line, the emergency dynamic braking circuit is established, and the series brakes set.

Many crane users prefer a power type overhoist limit switch, such as shown in Fig. 167. The contacts of the switch are connected directly in the motor power circuit, and connections are indicated by dotted lines in Fig. 325. When the limit switch is tripped by the hook block, its normally closed contacts between *S*1–*A*1 and *A*2–*R*20 close. The motor is thereby disconnected from the line, and the series brakes set, provided contactor 2*DB* is open. A dynamic braking circuit is established through the limit switch contacts and resistor *R*20–*R*21. No change takes place in the control circuit, and contactors stay closed, depending on the position in which the master switch happens to be.

Should the overtravel occur with the master switch in the first or second position, that is, with contactor 2*DB* closed, a circuit remains established through the series brakes, which stay released. When the limit switch trips, the load decelerates to a stop but owing to the effect of gravity it starts immediately to lower again, until the limit switch resets. Then hoisting connections are re-established, and the load is hoisted again until the limit switch trips. This oscillation of the load continues until the master switch is returned to the off position. Contactors *H* and *M* then drop out, and the series brakes set. The oscillation of the load described above, although not dangerous, can be avoided by the use of an additional current relay, connected in the motor armature circuit, which operates when the limit switch trips and causes 2*DB* to open when the master switch is in the first or second position.

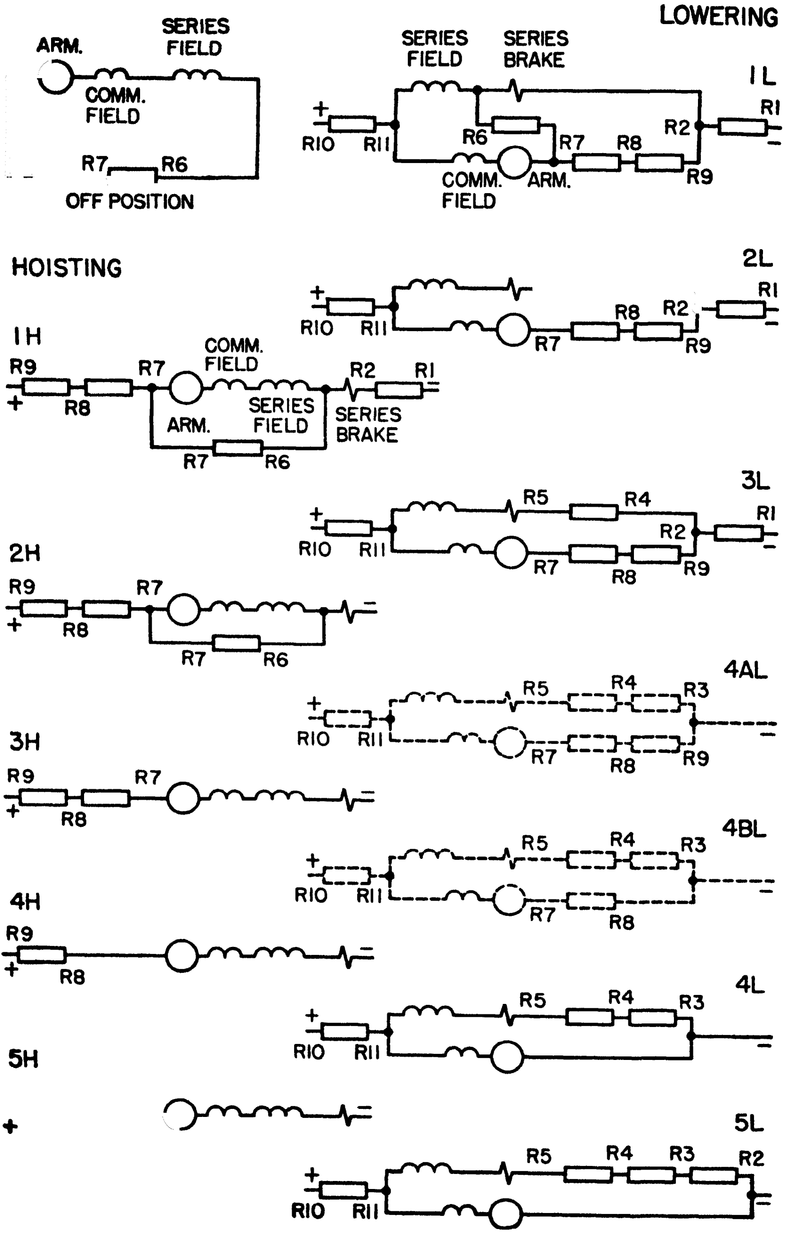


FIG. 326. Step-by-step power circuit diagram of dynamic braking crane hoist controller.

Lowering

On all master switch positions in the lowering direction, contactors *L* and 1*DB* are closed. Power is applied to the motor with the armature and field in parallel, and the lowering speed is controlled by varying the amount of resistance in the various branches of the motor circuit. Refer to Figs. 24 to 30 for the general shape of motor speed-torque curves obtained with this dynamic braking connection.

On the first master switch position, all resistance in series with the field is short-circuited, resistance in series with the armature is inserted, and section *R*1–*R*2 is in series with both the armature and the field. Contactor 2*DB* remains closed, which connects the series brakes and resistor section *R*6–*R*7 in parallel with armature series resistance *R*7–*R*9. This connection causes high current to be drawn through the series brakes, thereby insuring their release. The motor operates with a high field current, and performance is along curve 1–*L* of Fig. 327. Considering the reverse efficiency of the drive during lowering, the torque on the motor with a full load on the hook is somewhere between 0.6 and 0.8 per unit motor torque. Thus full load is lowered at approximately 0.3 per unit speed.

Moving the master switch to position two causes contactor 2*DB* to open. The effective resistance in series with the armature is increased. Motor performance is along curve 2–*L*, and motor speed is approximately doubled.

With the master switch in the third position, contactor 1*FW* is dropped out, and a block of resistance is inserted in series with the field. The field current is weakened and the motor speed increases. An interlock on 1*FW* interrupts the coil circuit of relay *CR*, which is of the magnetic time delay drop-out type and has the purpose of providing a time delay between the third and fourth step.

Turning the master switch to the fourth position drops out contactor 2*FW*, provided relay *CR* has dropped out. Another section of resistance is inserted in series with the field, causing further field weakening. Relay *CR* insures that, when the master switch is moved rapidly from the off position to the fourth position, field weakening takes place in two definite steps, and excessive armature current peaks are avoided. To limit the full-load speed under the weakened field condition to a safe value, contactors 1*A*, 2*A*, 3*A* close in this master switch position, placing the armature across the line in series with low-resistance division *R*10–*R*11 and making the field current substantially independent of load since high-resistance division *R*1–*R*2 is short-circuited by 1*A*. To insure that the accelerating contactors close when 2*FW* opens, the master switch contacts controlling 2*FW* and the accelerating contactors must overlap. This is important. Should the accelerating contactors fail to close when 2*FW* drops out, dangerous overspeeding of the motor may result.

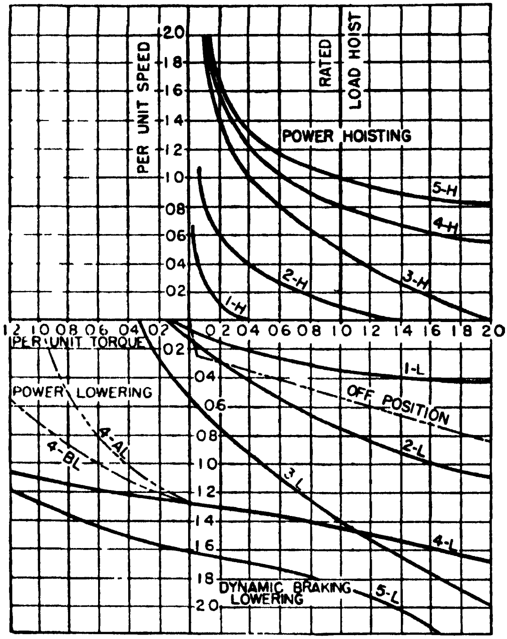


FIG. 327. Speed-torque curves of dynamic braking crane hoist controller.

Contactor 1*A* closes immediately when 2*FW* drops out. Contactors 2*A* and 3*A* close in time sequence, as governed by time delay drop-out accelerating relays 2*AR* and 3*AR*, which are also used to control acceleration in the hoisting direction. With large motors the time setting of 2*AR*, which obtains smooth acceleration hoisting plus the pick-up time of contactor 2*A*, may be so long as to permit overspeeding if a heavy load is lowered. On large hoist controllers, an additional accelerating relay 2*ARL* is used, the connections of which are indicated by dotted lines in Fig. 235. The coil of the relay is connected across the motor armature, and it is responsive to the motor counter emf. Thus the relay closes its contact when the motor attains a certain speed, and contactor 2*A* closes regardless of whether or not relay 2*AR* has timed out.

Motor performance is given by curve 4–*L* in Fig. 327. Acceleration to final speed takes place according to curves 4*A*–*L* and 4*B*–*L* which are obtained when contactors 1*A* and 2*A* close. The motor is capable of developing both dynamic braking torque and power torque. Thus an empty hook is lowered at high speed.

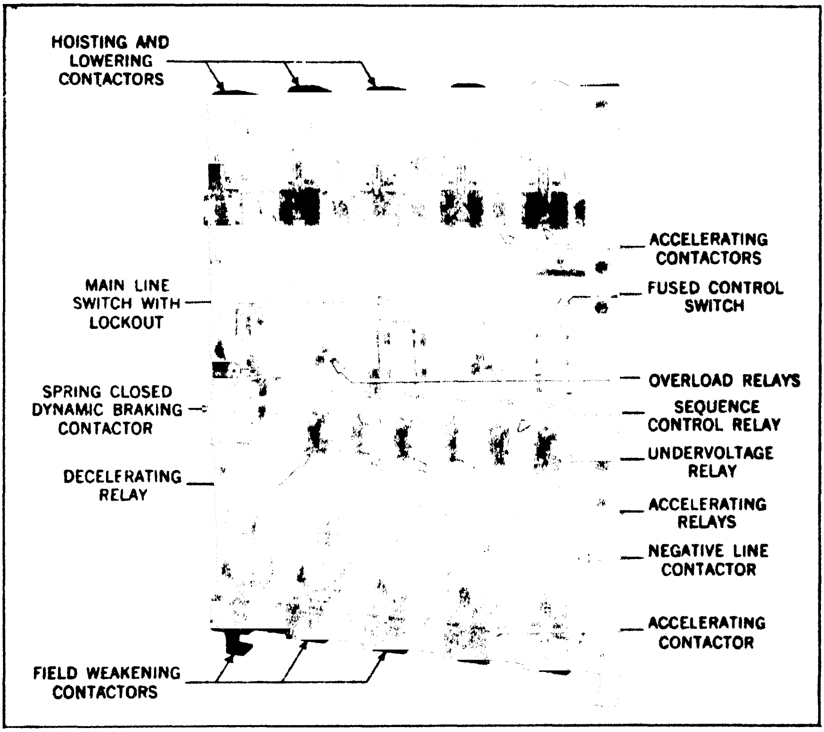


FIG. 328 Typical open type crane hoist control panel.

On the fifth and last master switch position, contactor 3*FW* opens and further weakens the motor field. The motor accelerates to its final lowering speed as given by curve 5–*L*. A normally closed interlock on 3*A* prevents 3*FW* from inserting the final field weakening block of resistance until after the accelerating contactors have closed and the armature is connected across the line. No matter how fast the master switch is turned to the fifth point, a definite sequence of acceleration in the lowering direction is enforced.

With the motor operating with weakened field on the fifth step, the problem of motor stability deserves consideration, as explained in Chapter 2. A block of resistance *R*10–*R*11 is inserted between contactor *L* and motor terminal *A*2. This resistor section stays in series with the motor on all steps lowering, and it has a considerable effect in obtaining a reasonably high break-down torque on the fifth master switch position.

During operation as a shunt generator, the energy delivered to the motor from the load must be dissipated as electric energy. Resistance connected in series with the armature on the first, second, and third master switch positions absorbs this energy. On the fourth, and especially the fifth position, part or all of the energy delivered to the armature supplies a certain portion of the field excitation. With heavy loads, some energy is pumped back into the line. The amount of pump-back is governed largely by the amount of field weakening used. The more the field is weakened, which means the higher the lowering speed at full load, the more current is pumped back into the line. When hoist controllers are connected to individual power plants, for instance to Diesel engine-driven generators on floating cranes, the amount of field weakening and correspondingly the lowering speed must be reduced to such a value as not to cause pump-back with the heaviest loads encountered, because such power plants cannot absorb pump-back energy.

A similar situation exists when cranes are connected to rectifiers without other power consumers which could absorb the pump-back energy. Either the crane lowering speed must be limited to a sufficiently low value to prevent pump-back, or a protective resistor must be connected across the rectifier bus when a pump-back condition arises. An overhauling load on a rectifier bus causes a rise in line voltage, which can be used as a signal to connect the protective resistor to the line as long as a pump-back condition exists.

Overtravel protection in the lowering direction is provided only on rare occasions, as the floor generally stops downward travel of the load. There are cases which require a definite limit in the lowering direction, for instance, hoists which raise and lower the booms of shipyard cranes. Control type limit switches are then used and circuits are arranged so that contactors *L*, 1*DB*, 2*DB* are dropped out, setting the brakes and establishing the emergency dynamic braking circuit.

Automatic Deceleration

Stopping the load involves problems peculiar to hoists. When the load is to be stopped during hoisting, gravity decelerates load. The motor is simply disconnected from the line and the mechanical brakes set. The brakes have to dissipate only part of the stored energy of the moving system since gravity assists the brakes in stopping the load.

An entirely different condition exists when a load which is being lowered is to be stopped. Not only has the total kinetic energy of the load to be dissipated, but in addition the pull of gravity has to be overcome. Stopping the load from full speed by the mechanical brakes only would impose a severe duty on the brakes, resulting in short life of the brake linings. It is preferable to let the motor retard the load by dynamic braking before the mechanical brakes are applied. The kinetic energy of a moving mass is proportional to the square of its speed. If, for instance, the speed of the load is reduced to one quarter of full lowering speed by dynamic braking, only one sixteenth of the kinetic energy is left to be absorbed by the mechanical brakes.

The control connections of Fig. 325 include an automatic decelerating sequence, when the load is stopped from a high lowering speed. A decelerating relay *DR* is provided, the coil of which is connected across field resistor section *R*2–*R*5. With the master switch in the fourth or fifth position, the relay is picked up and its contacts are closed. When the master switch is returned rapidly to the first position or to the off position, *DR* relay coil is de-energized by the closing of contactor 1*FW* or the opening of contactor *L*. As *DR* is of the magnetic time delay drop-out type, it stays picked up for an adjustable time interval and maintains control circuits to hold contactor 1*DB* closed and 2*DB* open, regardless of master switch contact conditions. The motor decelerates at first with a dynamic braking loop circuit containing the armature, field, brake coils, and resistor section *R*7–*R*9, and the brakes are held released. The timing of *DR* is adjusted so that it drops out when the load has decelerated to approximately one quarter of full speed. When *DR* drops out, 1*DB* opens and 2*DB* closes. The emergency dynamic braking circuit is then established and the brakes set. A resistor having a resistance of approximately three times the coil resistance is connected in parallel with the coil of 1*DB*, giving that contactor a slight time delay on drop-out. A capacitor of 0.5 to 1 microfarad is connected in parallel with 2*DB* coil, resulting in fast drop-out due to suppression of arcing on *DR* contact. Thus a slight overlapping of 1*DB* and 2*DB* is obtained, and the dynamic braking loop circuit is never interrupted.

Grab Bucket Hoist Control[6]

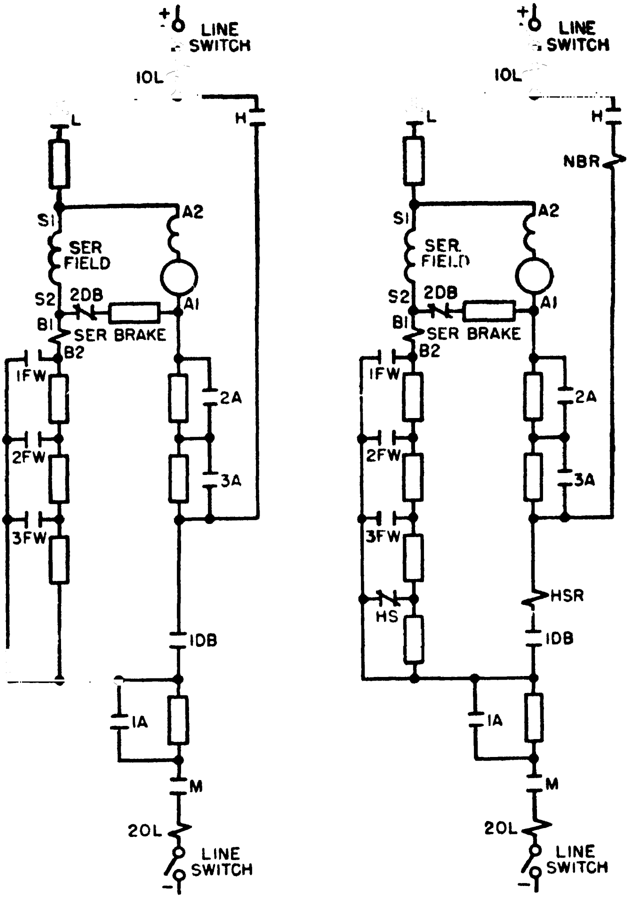
Grab bucket hoists contain two drums, one for the holding line and one for the closing line. Opening and closing of the bucket is accomplished by relative motion between the two lines. Pulling on the holding line or paying out rope on the closing line opens the bucket. Pulling on the closing line or paying out rope on the holding line closes the bucket. Either the open or the closed bucket can be hoisted or lowered by hoisting or lowering both lines simultaneously.

Grab bucket hoists are driven either by a single motor or by two motors. In the case of a single-motor hoist, relative motion between holding and closing line drums is obtained by clutches and band brakes which permit turning either or both drums by the motor. As far as control is concerned, any standard hoist controller which provides electric braking is satisfactory and the control of clutches and drum brakes is extraneous to the motor control. It is up to the operator to manipulate the two drums so as to load and dump the bucket.

Two-motor hoists have one motor coupled to each drum and there is no mechanical tie between drums. These two motors are generally referred to as the holding motor and the closing motor. Each motor has its separate control panel and master switch. Relative motion between drums is obtained by manipulating either or both master switches. The dynamic braking hoist circuit of Fig. 325 can be used for grab bucket work, provided that some modifications are made in the control of the closing line motor.

Shown in Fig. 329 are the elementary power circuits of a two-motor grab bucket hoist. The holding line circuit is the same as that of Fig. 325. The closing line circuit contains several additional devices necessary to obtain proper control of the bucket. For an illustration of hoist performance, see Fig. 330, in which the speed-torque curves of both the holding line and closing line motor are plotted.

In the hoisting direction, both motors operate in straight series connection, and the performance curves for both motors are alike. With the bucket resting on the pile a load is picked up by pulling on the closing line only, until the bucket is closed. Then the full bucket is hoisted by the holding and closing lines which divide the load evenly. A careless operator might attempt to lift the bucket off the pile with the closing line only, leaving excessive slack in the holding line, which would throw twice normal load on the closing line motor and ropes. To avoid this contingency, a current type notch-back relay *NBR* is connected in series with the closing line motor armature. If the current drawn by the closing line motor



HOLDING LINE CLOSING LINE

FIG. 329. Power circuits of grab bucket hoist with shunt generator dynamic braking lowering. Nomenclature of devices and contactor closing sequence same as in Fig. 325, except that the following are added to the closing line: *HS*. High-speed contactor, opens on fifth master switch position when lowering empty bucket. *HSR*. Load responsive high-speed relay, controls opening of *HS*. *NBR*. Notch-back relay, prevents hoisting of full bucket with closing line only.

exceeds approximately 150 per cent of normal, accelerating contactors 2*A* and 3*A* are dropped out, and the closing line slows down or even stalls. The holding line motor, carrying light load, accelerates to full speed and takes up the slack in the ropes. When the holding line is taut and takes its shares of the load, *NBR* drops out and permits the closing line motor to reaccelerate.

In the lowering direction, both motors have their field connected in parallel with the armature. The resistor lay-out for the two motors is slightly different so that with full-load torque the closing line speed is slightly lower than the holding line speed, in order to assure that a loaded bucket, while being accelerated and decelerated, has no tendency to crack open and spill its load, as the closing line takes a slightly higher load than the holding line. The lowering curves of Fig. 330 are typical as far as their general shape is concerned. Actual speeds may vary somewhat, the maximum lowering speed corresponding to the fifth master switch position being determined by bucket design and the specified duty cycle.

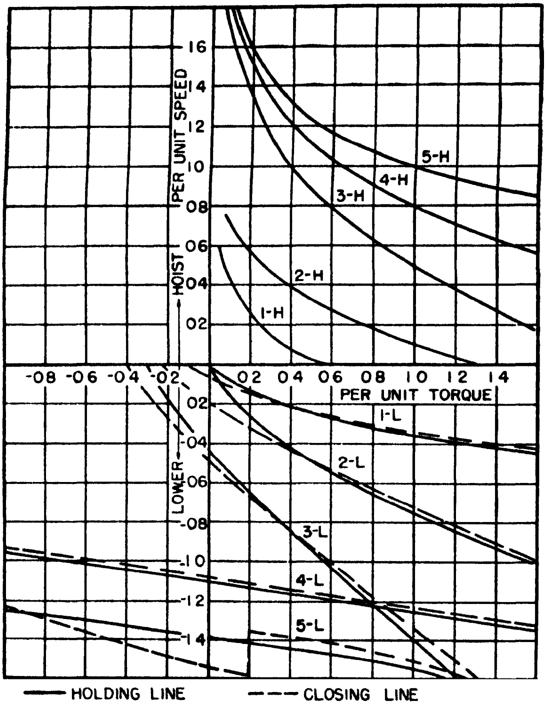


FIG. 330. Speed-torque curves of grab bucket hoist controller with connections in accordance with Fig. 329.

Good control requires not only that a loaded bucket be lowered without opening but also that an open bucket be lowered without drifting closed. Thus in the region of light-load torques the closing line speed is higher than the holding line speed on the fifth master switch position. An additional contactor *HS* controls a section of resistance in series with the closing line motor field. With *HS* open, the closing line motor field is weakened more than the holding line motor field. On the fifth master switch position, *HS* is controlled by relay *HSR*, which responds to the motor armature current and is set to pick up when the motor torque exceeds about 0.2 per unit torque.

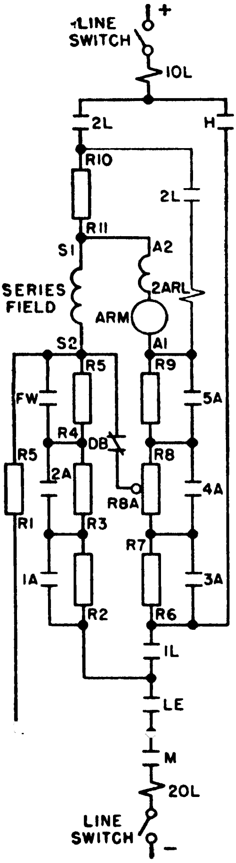
When an open bucket is about to be lowered, the holding line is taut and the closing line is slack. The closing line carries no load and relay *HSR* does not pick up. Contactor *HS* opens, the closing line motor performs along the left half of curve 5–*L*. Therefore, the holding line supports the bucket and the closing line drum merely pays out rope; the bucket has no tendency to close. If, however, a loaded and closed bucket is to be lowered, it hangs in both lines, which are taut. Thus the closing line initially carries approximately full load, and relay *HSR* picks up. Contactor *HS* is prevented from opening, and closing line motor performance is along the right half of curve 5–*L*. The closing line motor takes a slightly higher load than the holding line motor, and the bucket cannot open.

Making *HS* a spring-closed contactor is dictated by considerations of safety. A coil failure would prevent *HS* from opening, and an open bucket would close during lowering. It is a lesser evil than if *HS* were normally open, and a coil failure would cause a closed bucket to open and spill its load while being lowered.

Dynamic Braking as Series Generator for Grab Buckets

In Chapter 2, Fig. 22, it is shown that a series motor, with field and armature connected in series with each other through a resistor, acts as a series generator and develops a torque suitable for retarding an overhauling load. The lowering speed can be controlled by varying the amount of resistance in the loop circuit. This method of dynamic braking lowering is not suited for general-purpose crane hoists because the speed-torque curves do not cross from quadrant 4 into quadrant 3 and the series generator connection does not provide driving torque necessary to lower an empty hook. On grab bucket hoists, however, the series generator connection can be used to advantage because maneuvering of light loads is not required. The hoist motor is either well loaded or it is completely unloaded for paying out line, but this operation does not require accurate spotting.

Figure 331 is the elementary power diagram of a single-motor grab bucket hoist controller, and a contactor closing sequence table is included. A corresponding step-by-step power diagram is given in Fig. 332, and the speed-torque curves are plotted in Fig. 333. Series brakes cannot be used because there is no circuit branch carrying sufficient current to obtain brake release under all operating conditions. Shunt wound solenoid brakes or air-operated brakes must be used, which are released whenever the master switch is moved out of the off position.



NOMENCLATURE OF DEVICES

M	MAIN LINE CONTACTOR
LE	LINE CONTACTOR
H	HOIST CONTACTOR
1L,2L	LOWER CONTACTORS
DB	DYNAMIC BRAKING CONTACTOR
1A 2A 3A 4A 5A	FIRST SECOND THIRD FOURTH FIFTH } ACCELERATING CONTACTORS
FW	FIELD WEAKENING CONTACTOR
1OL,2OL	OVERLOAD RELAYS
2ARL	ACCELLERATING LOWER RELAY

CONTACTOR CLOSING SEQUENCE

	LOWER					OFF	HOIST				
	5	4	3	2	1		1	2	3	4	5
DB						X					
M	X	X	X	X	X		X	X	X	X	X
H							X	X	X	X	X
LE	X						X	X	X	X	X
1L	X	X	X	X	X	X					
2L	X	X	X	X	X						
1A	↗		X	X	X	X		X	X	X	X
2A	↗			X	X	X			X	X	X
3A					X	X				X	X
4A					X	X					X
5A											X
FW		X	X	X	X	X	X	X	X	X	X

CLOSE ON FIFTH POSITION LOWER UNDER CONTROL OF RELAY 2ARL

FIG. 331. Power circuits of grab bucket hoist with series generator dynamic braking lowering.

In the hoisting direction, the motor operates as a straight series motor. In the first four positions lowering, the motor is connected as a series generator, and speed is controlled by varying the amount of resistance in the dynamic braking loop circuit. The motor circuit is

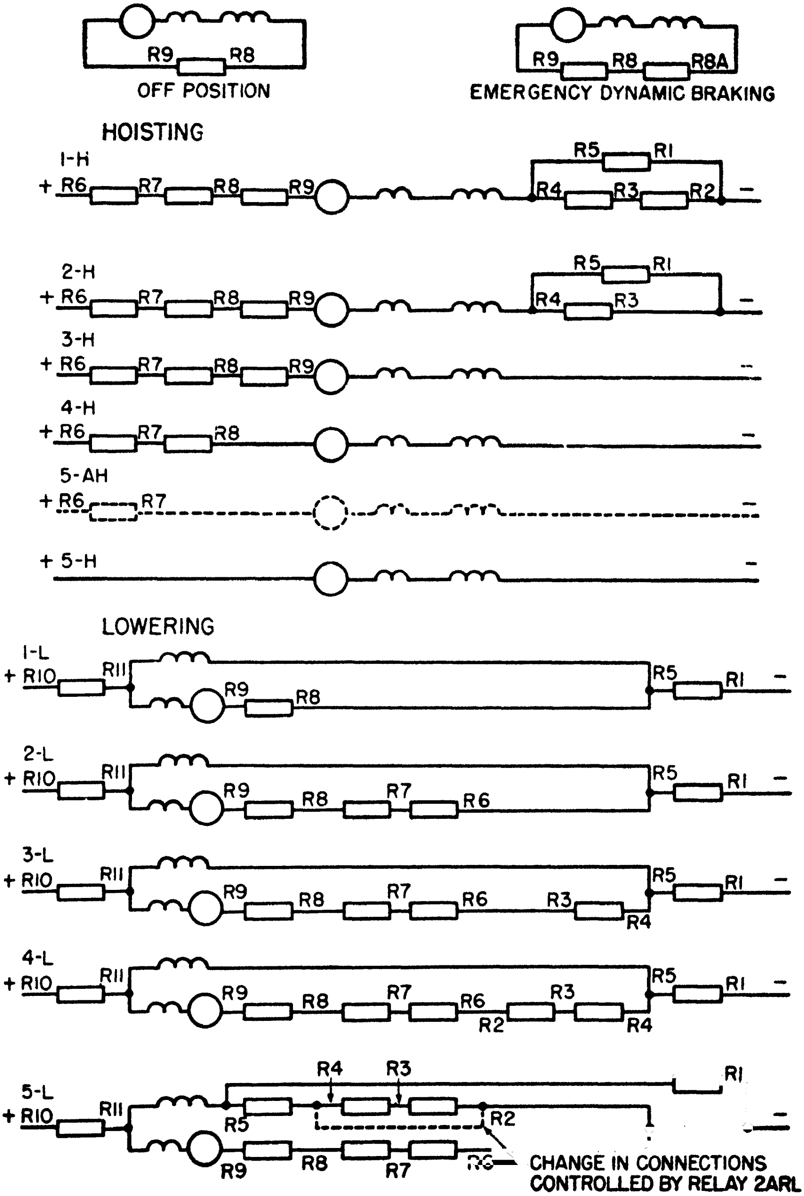


FIG. 332. Step-by-step power circuit diagram of grab bucket hoist controller in accordance with Fig. 331.

connected to the line through resistor section $R1$–$R5$, which contains approximately ten times normal ohms. This high resistance has a negligible effect on the speed-torque curves, but it insures a trickle of current through the field in the correct direction to insure that self-excitation takes place.

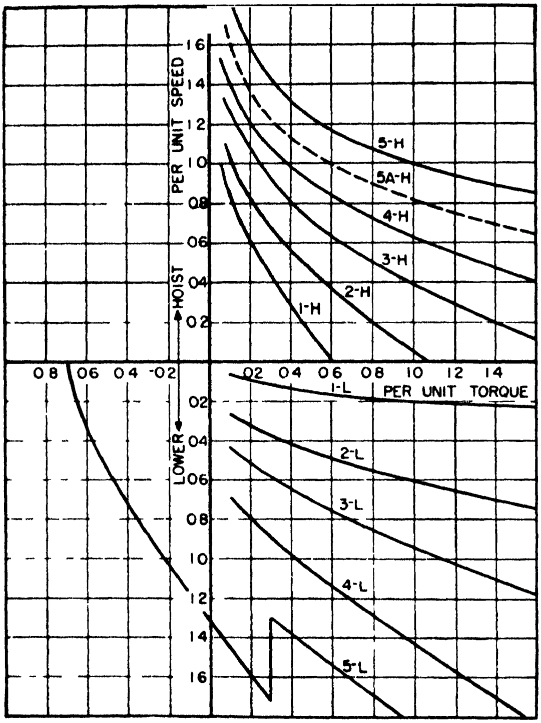


FIG. 333. Speed-torque curves of grab bucket hoist controller in accordance with Fig 331.

Motor connections are changed in the fifth master switch position to a shunt generator connection, with armature and field in parallel. The purpose is to obtain driving torque from the motor which is necessary to pay out line and open the bucket quickly. A latch in the master switch handle or a foot-operated switch is used to establish motor connections corresponding to the fifth step, regardless of master switch position, thereby obtaining quick acceleration or "kick-off" of the load. Curve 5–L in Fig. 333 is a composite of two curves, and switch-over occurs at approximately 0.3 per unit torque. The left part of the curve corresponds to connections with contactors 1A and

2*A* open. When the speed reaches a predetermined value, relay 2*ARL* picks up and causes contactors 1*A* and 2*A* to close, and motor performance is along the right part of curve 5–*L*. Relay 2*ARL* is connected across the motor armature, and it picks up when the motor counter emf, which is a measure of speed, reaches approximately 80 per cent of line voltage.

Curve 5–*L* of Fig. 333 is much steeper than the corresponding lowering curve of the previously described crane hoist controller. Such a curve would be rather undesirable for general-purpose crane hoists, as a wide variation in loads and possible overloads would cause great variations in speed. On grab bucket hoists, the load is quite definite, and a bucket cannot be loaded beyond a known amount, the maximum possible load being determined by the physical dimensions of the bucket. Also accurate jogging or spotting is not required, and thus a steep lowering curve is quite acceptable.

The control system described above can also be applied to two-motor hoists. Controllers for the holding and closing lines are substantially alike. The resistor lay-outs are somewhat different, so that the lowering curves for the closing line are slightly above the corresponding curves for the holding line. Also, the previously described

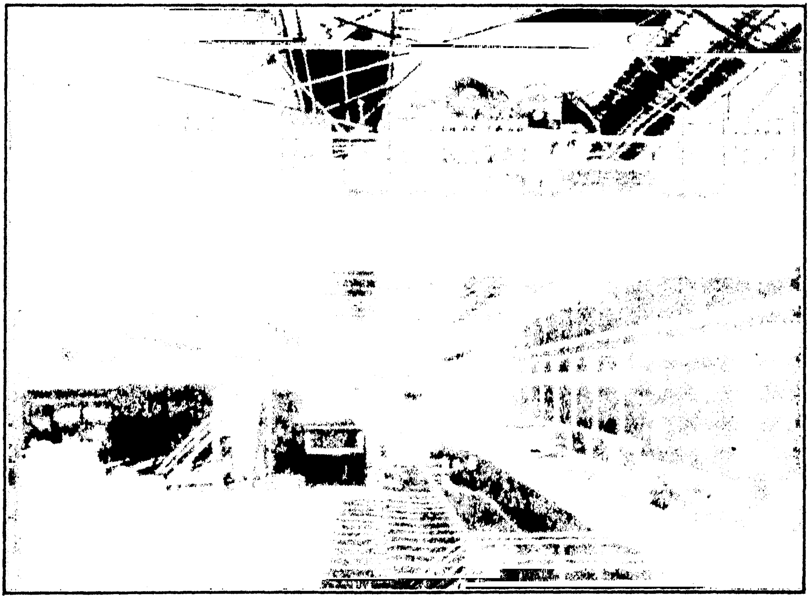


FIG. 334. Typical installation of open control panels on bridge of traveling crane.

notch-back relay and load-discriminating relay are added to the closing line control.

Controller Installation and Construction

Many controllers for cranes and steel mill auxiliaries are conventional as far as their construction and installation are concerned.

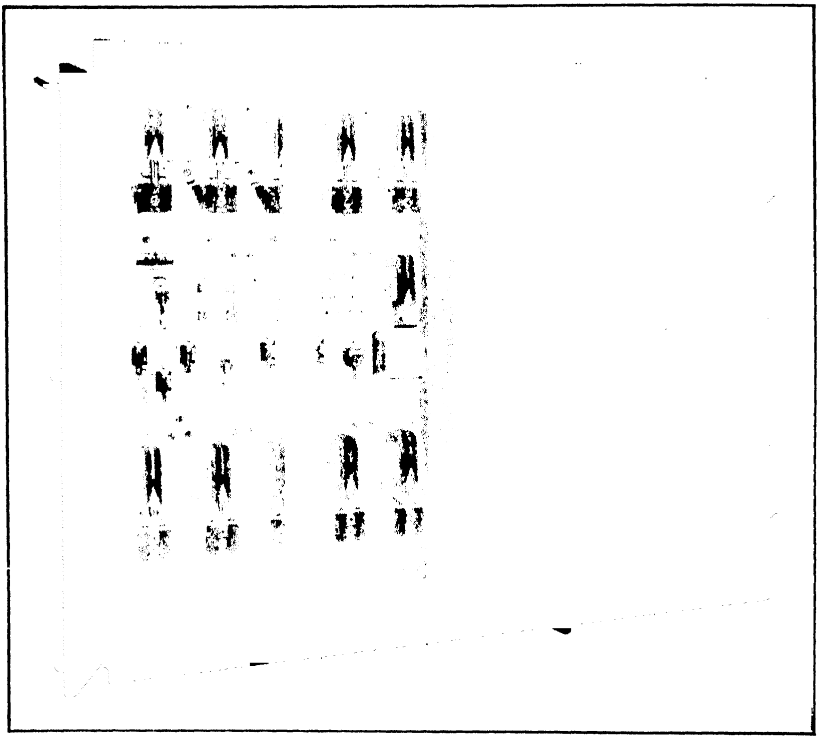


FIG. 335. Crane control panel of unit base construction in heavy type *IA* enclosing case.

Open or enclosed panels may be used, depending on local conditions. Panels for mill auxiliaries may be grouped into unit-assembled frameworks (see Figs. 202 and 203) where space permits, or they may be mounted as individual panels near the driven machinery. On cranes space is at a premium, and individual panels are generally used for each motion. On traveling cranes, panels and resistors are mounted on the bridge. Figure 334 shows a typical installation of open type individual panels of standard construction, mounted on the bridge of a traveling crane in a steel mill.

On some cranes and related machines, the control equipment is subjected to a considerable amount of vibration, and trouble may be experienced because of breakage of bases. Unit base assembly, where each contactor or a group of light-weight devices are mounted on their individual bases, provides a considerable degree of insurance against breakage due to vibration. Shown in Fig. 335 is a crane control panel, built of unit bases, which are bolted to a supporting framework. The whole panel is enclosed in a gasketed type 1A enclosing case of heavier than normal construction, with latches to keep the doors tight. Such construction is suitable, for instance, for ingot handling cranes which are exposed to a considerable amount of semiconducting dust.

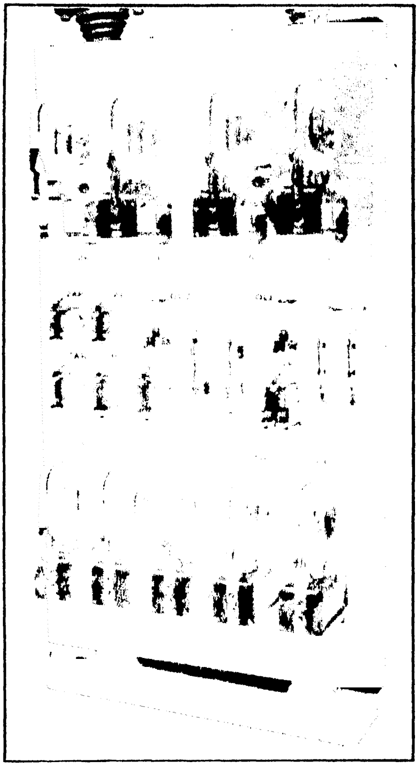


FIG. 336. Control panel of unit base construction with spring supports for ingot buggy.

Even such construction may not be good enough for such applications as charging machines or ingot buggies on which the control is subjected to severe vibration and shock. As a solution, the panel shown in Fig. 336 is constructed of unit bases, which are clamped to a steel frame, avoiding any mounting holes in the bases. The whole panel is supported by heavy coil springs from the top and bottom.

Floor-Operated Cranes

Small cranes for general shop use may be operated from the factory floor by means of pendant type push or pull buttons or master switches, suspended from the crane bridge or trolley by a flexible cable. The motor ratings involved are smaller than for cab-operated cranes, and they should not exceed 35 hp. Such cranes do not warrant elaborate control as customarily used on the larger cranes, and

NEMA Standards include recommended practices applying to small cranes.

Contactors may be of a smaller continuous rating than 100 amperes, which is the smallest size permitted for cab-operated cranes. Table 28 gives the contactor rating in horsepower and the recommended minimum number of accelerating contactors to be used.

TABLE 28

CONTACTOR RATING FOR FLOOR-OPERATED D-C CRANES

Standard 8-Hour Rating in Amperes	*Crane Rating*		*Minimum Number of Accelerating Contactors*	
	Amperes	*Horsepower at 230 Volts*	*Hoist*	*Bridge and Trolley*
25	25	5	2	1
50	50	15	2	2
100	133	35	3	3

NEMA also recommends that the following features be included in floor-operated crane controllers:

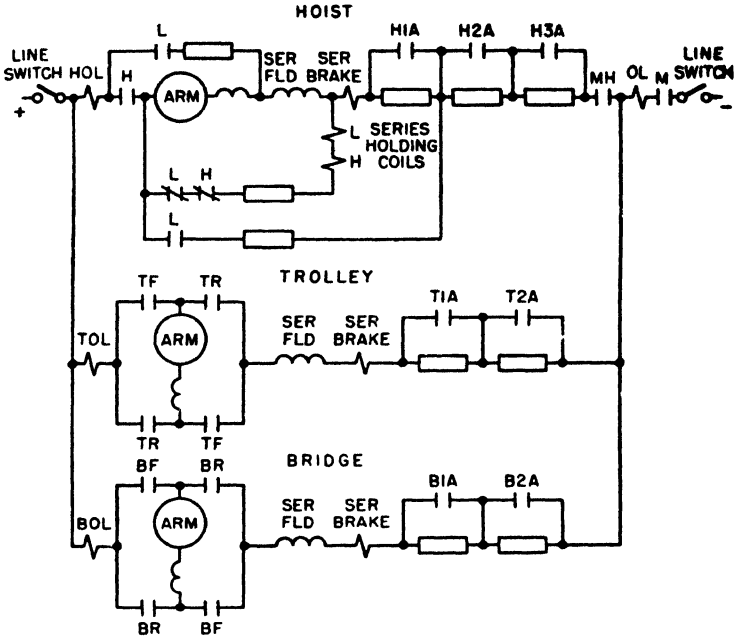
1. The control for hoists should provide dynamic braking lowering.
2. Bridge and trolley controllers should provide plugging protection, and the first accelerating contactor could be used as a plugging contactor.
3. Accelerating contactors should close in sequence under the control of automatic accelerating means.
4. Controllers may be built with or without motor protection. If protection is included, directional contactors and a negative line contactor open both sides of the line, and control circuits are arranged so that undervoltage protection is obtained. Overload relay coils are connected in the positive line to each motor and in the common negative line.
5. Resistors are NEMA class 153 for the hoist, class 154 for the bridge, and class 155 for the trolley.
6. When operated by a pendant button station, the following buttons are provided as a minimum on the three-motion crane:

Hoist	Bridge forward	Trolley forward
Lower	Bridge reverse	Trolley reverse

If protection is included in the controller, the following buttons are included:

Emergency stop	Reset

As an optional item, additional hand-controlled speed points may be added for any or all motions. It may be done by adding extra buttons for high and low speed or by using master switch units which



CONTACTOR CLOSING SEQUENCE

HOIST

	LOWER			OFF	HOIST		
	3	2	1		1	2	3
MH	X	X	X		X	X	X
H					X	X	X
L	X	X	X				
H1A						X	X
H2A		X	X				X
H3A			X				X

TROLLEY BRIDGE

	FOR			OFF	REV			
	3	2	1		1	2	3	
TF	X	X	X					BF
TR					X	X	X	BR
T1A	X	X				X	X	B1A
T2A	X						X	B2A

FIG 337 Power circuits of floor-operated crane.

close contacts in sequence, depending on the distance the button is pushed in, or the units may be lever- or pull-handle-operated.

Figure 337 is a typical elementary power circuit diagram of a floor-operated traveling crane, containing hoist, trolley, and bridge motion. The circuits contain the essential elements of corresponding cab-operated crane controllers but in a simplified manner. The hoist control includes dynamic braking lowering with shunt generator connection and speed control by varying the amount of resistance in series with the armature. The emergency dynamic braking circuit, which also provides deceleration during stopping, is established through normally closed back contacts on contactors *H* and *L*. To insure good contact pressure, holding coils (see Fig. 226*E*) are used which are connected in the dynamic braking loop circuit. Control for the trolley and bridge are of the reversing type. Plugging is possible, provided the resistor includes sufficient resistance.

The contactor closing sequence table is based on the assumption that a three-position master station is used. Depending on the details of the control circuits, the crane may be operated by a variety of master stations. In the simplest case, a pendant push button station is used which contains two buttons for each motion, one for each direction of rotation. Only one speed is then available, and contactors are closed as indicated for position three of the sequence table.

Automatic timing relays must be included in the controller to obtain proper closing sequence of accelerating contactors.

As an added refinement, two push buttons may be used for each direction of rotation on one or all motions, one button for slow speed and one button for full speed. The slow-speed button would obtain power connections corresponding to position one of the sequence table, and the full-speed button would obtain connections corresponding to position three. Fast and slow buttons are often used on hoists to assist in spotting the load. They are quite frequently used on the bridge, but seldom on the trolley, the full speed of which is generally slow enough to permit accurate jogging with the full-speed button only.

During the past few years a number of pendant master stations have appeared on the market which provide for several speed positions. One design consists of push button units which contain a series of contacts. They are closed in sequence, depending on how far the button is pressed, thus giving the operator means to select operating speed by varying pressure on the button. Another design includes miniature drum type master switches with several positions. They are operated by a small thumb lever, and they are returned to the off position by a spring. A form of master station, which includes inherent time delay sequence of contact operation and eliminates separate time delay accelerating relays, is shown in Fig. 338. The complete station contains a number of units, one for each direction of travel of each motion. To operate the unit, the handle is pulled out. Internal construction details are given in the cut through the unit. Pulling the handle actuates a piston which works against an air dash-pot and causes contacts to close with a definite time delay between them.

Protection is provided by main line contactor *M* which is common to all motions. For this contactor, the control station contains momentary contact "stop" and "reset" push buttons. Pressing the stop button drops out *M* and removes power from the crane. *M* also drops out in case one of the overload relays trips or voltage is lost. To reapply power to the crane, the reset button must be pressed to close *M*, thus undervoltage protection is obtained. Overtravel protection may be included by conventional control or power type limit switches.

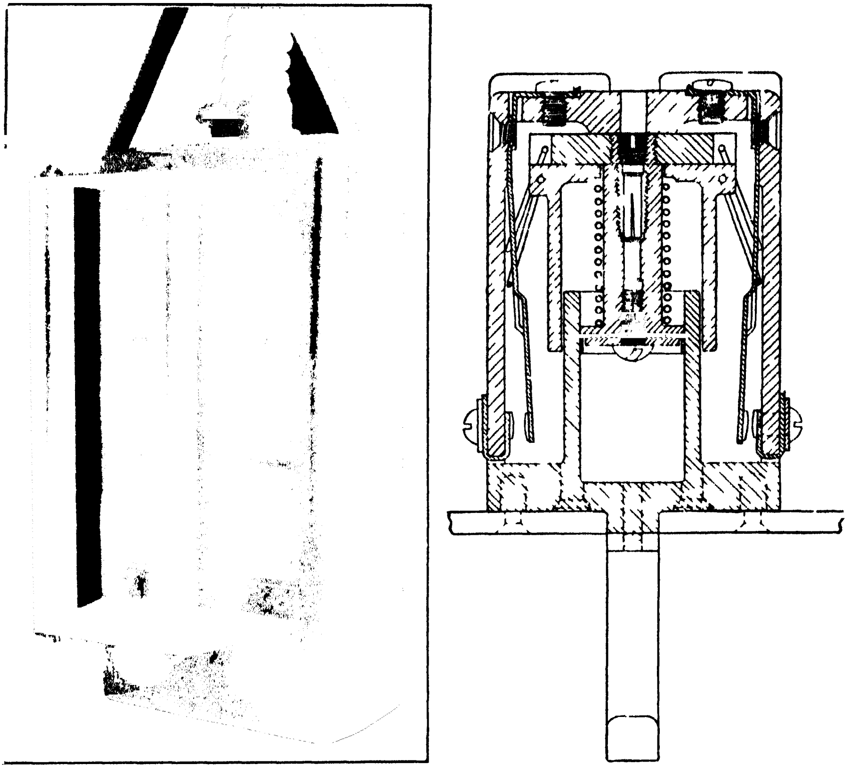


FIG. 338. Pendant master station for floor-operated cranes. *A*, Complete station. *B*, Section of individual control unit.

A typical enclosed control panel for a floor-operated traveling crane is shown in Fig. 339. Panels are generally mounted on the bridge. Because of limited headroom they are built low and wide. The lifting channel across the top may be removed after the panel has been installed. Access to the panel devices and the wiring is provided by removable cover plates, as there is generally not sufficient room on the crane for swinging door. The panel contains all the necessary contactors for the three motions. The resistors are included as part of the panel, and all resistor connections are made at the factory.

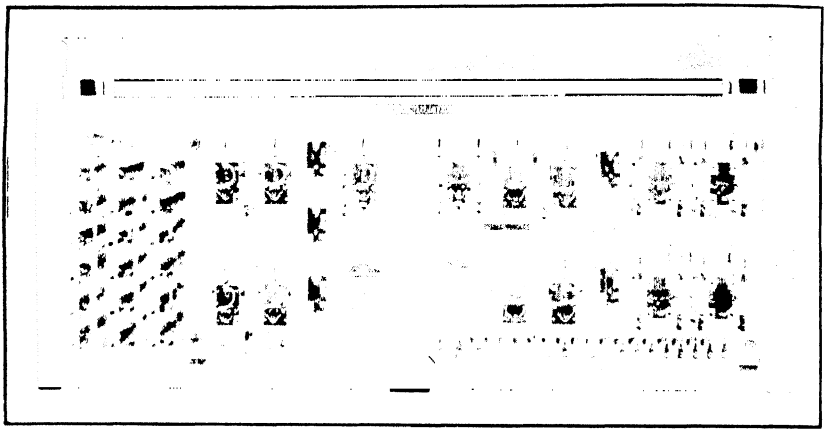


FIG. 339. Enclosed control panel for floor-operated traveling crane.

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CHAPTER 19

ALTERNATING-CURRENT INTERMITTENT-DUTY CONTROLLERS

The general comments in the preceding chapter on d-c intermittent-duty controllers apply also to a-c intermittent-duty controllers. As there are comparatively few a-c mill auxiliaries in existence, NEMA has not established any standards for a-c auxiliaries in steel mills. The great majority of intermittent a-c drives are on cranes and related material-handling equipment. Although a-c motors are inherently less flexible and versatile than d-c motors, they have of late been used in large numbers in industry for applications which had previously been considered a domain of d-c motors. Since a-c power is generally available wherever industrial plants are in existence, the use of a-c motors has the advantage that conversion equipment is unnecessary. Progress has been made in devising control systems which permit controlling the speed and torque of a-c motors under a variety of load conditions. The ones most generally used are described in this chapter. As cranes involve the greatest diversity of service conditions, this discussion is based essentially on crane practice.

Cab-Operated Cranes

As in the case of d-c applications, two basic types of controllers are used on a-c cranes. One type is used primarily on bridge and trolley travel motions requiring starting and stopping and absorbing the kinetic energy of the masses by electric braking, usually plugging. The second type of controller is used on hoists and includes means to retard an overhauling load. This retardation may be accomplished by plugging or various methods of dynamic braking.

Contactors for crane control panels are applied on the basis of their NEMA short-time ratings as given in Table 9 (page 180). Primary contactors are selected in accordance with the horsepower rating of the table. Two-pole secondary contactors have a crane rating of not less than the full-load secondary current of the motor. If three-pole secondary contactors are used delta-connected, the actual secondary current of the motor may be 1.5 times the crane rating of the contactors.

NEMA has also standardized the number of accelerating contactors to be used on crane control panels. They are listed in Table 29. Any low-torque or plugging contactors which may be used on a controller are in addition to the accelerating contactors listed in the table.

TABLE 29

NUMBER OF ACCELERATING CONTACTORS USED ON A-C CRANE CONTROL PANELS

Motor Horsepower Rating	*Minimum Number of Accelerating Contactors*
15 hp and less	2
16 to 75 hp	3
76 to 200 hp	4
Above 200 hp	5

Practices recommended by NEMA include the following features, which are included in standard a-c crane controllers:

1. A disconnect switch, opening all phases of the supply system, is provided on each individual control panel or on a protective panel. The current rating of the switch is not less than the 8-hour rating of the line contactor with which it is associated. Means for locking the switch in the open position are included as a safety measure.
2. Overload and undervoltage protection are included either on each control panel or on the protective panel. On a two-phase system, the overload relays protect each phase. On a three-phase system, they protect two phases. Instantaneous relays are commonly used to protect against excessive current and torque peaks.
3. The same standards, as given in Chapter 18 apply to the master switch handle throw.

Crane Protective Panels

Standard crane protective panels include the following equipment:

One knife switch with lockout, with sufficient poles to open all phases of the power system.

One line contactor with sufficient poles to open all phases of the power system.

One set of automatically reset overload relays, one double-coil relay or two single-coil relays for each motor.

Two pilot light receptacles and fuses.

Two control circuit fuses.

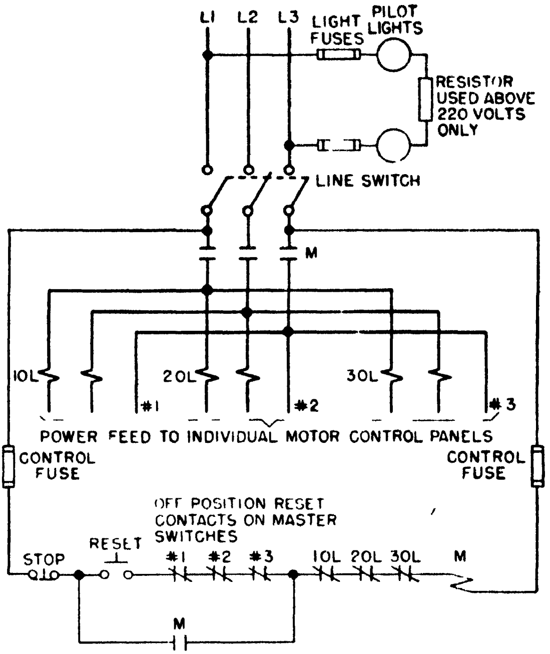

L1
L2
L3
LIGHT FUSES
PILOT LIGHTS
RESISTOR USED ABOVE 220 VOLTS ONLY
LINE SWITCH
M
1OL
2OL
3OL
#1
#2
#3
POWER FEED TO INDIVIDUAL MOTOR CONTROL PANELS
CONTROL FUSE
CONTROL FUSE
OFF POSITION RESET CONTACTS ON MASTER SWITCHES
RESET
STOP
#1 #2 #3
1OL 2OL 3OL
M
M

FIG. 340. Connections of a-c crane protective panel. *M* Line contactor. *1OL*, *2OL*, *3OL*. Individual motor overload relays.

One momentary contact "reset-stop" push button station for control of the line contactor, mounted separately from the panel.

The size of the line contactor of protective panels is governed by the following:

1. The 8-hour rating shall be not less than 50 per cent of the combined intermittent-current rating of all motors or less than 75 per cent of the sum of the intermittent-current ratings of the motors required for any single crane motion.
2. In no case shall the line contactor be of a smaller rating than the largest motor primary contactor used on any of the panels protected thereby. For motors of standard voltages, NEMA

has published the ratings given in Table 30 for protective panel line contactors.

Figure 340 is an elementary diagram of a typical three-motor crane protective panel. Two pilot lights are connected across the power line ahead of the line switch to indicate that power is available. On 220-volt circuits, two standard 110-volt lamps are used in series. On higher voltages, a resistor is connected in series with the lamps. Off position reset contacts of the master switches for the individual motions are connected in series with the reset push button. Thus the line contactor can be closed only when power is removed from all motors. In case of an overload on any motor, power is removed from all motors.

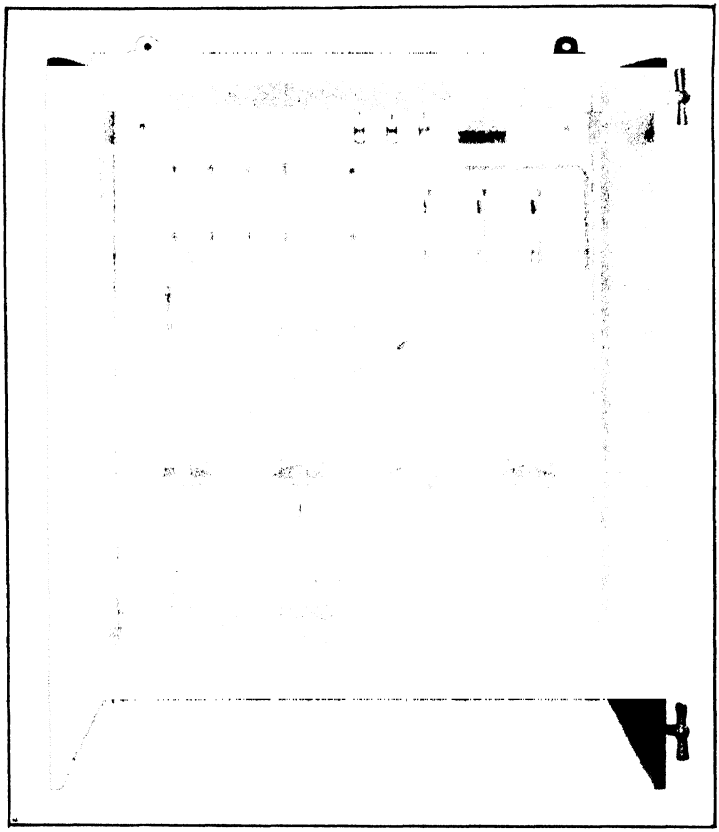


FIG. 341. Enclosed a-c crane protective panel.

TABLE 30

NEMA RATING OF LINE CONTACTORS FOR A-C CRANE PROTECTIVE PANELS

Standard 8-Hour Ampere Rating	*Total Horsepower All Motors*		*Largest Individual Motion Horsepower*	
	At 220 Volts	*At 440 and 550 Volts*	*At 220 Volts*	*At 440 and 550 Volts*
50	30	60	15	25
100	65	125	40	75
150	110	225	60	125
300	225	450	150	300
600	450	900	300	600
900	675	1350	450	900

Protective panels may be open or a front cover may be included as protection for the operator or they may be totally enclosed. Figure 341 is a view of a typical enclosed protective panel.

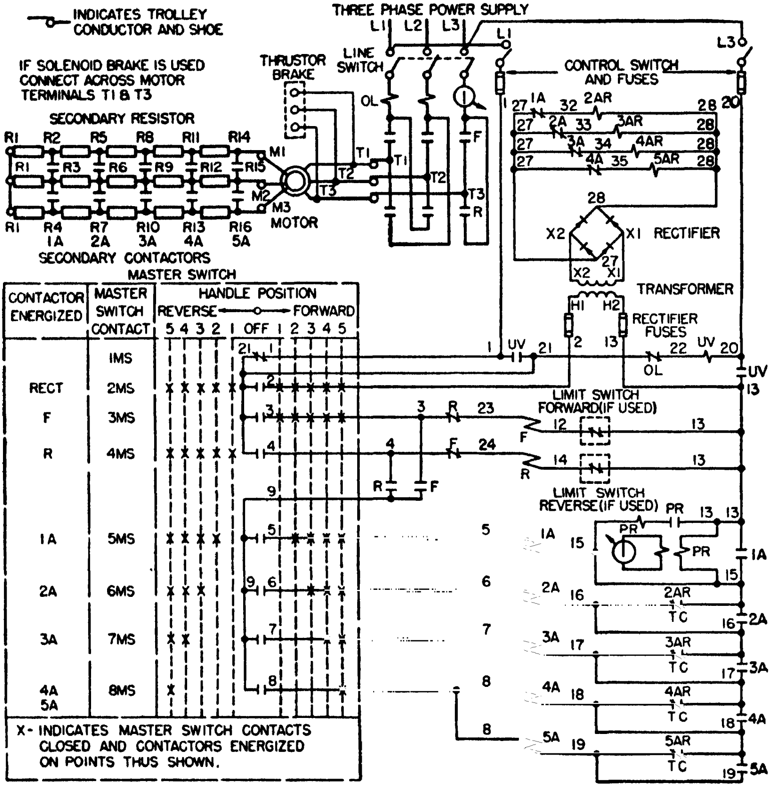
Reversing Hoist and Travel Controllers

The most widely used a-c crane controllers are of the straight reversing type, with or without plugging. The basic circuits required for a plugging controller are explained in Chapter 12 (see Fig. 248). The elementary connections of a complete crane controller are shown in Fig. 342. In accordance with NEMA recommended practice, the control panel contains the following devices:

- One line switch (triple-pole for three-phase system) with provision for locking in the open position.
- One double-pole control circuit switch and fuses.
- One double-coil (or two single-coil) automatically reset overload relay.
- One undervoltage relay.
- One pair of reversing contactors (opening all lines) electrically and mechanically interlocked.
- One plugging contactor with means for automatically preventing its closing unless motor is at some reduced speed.
- One set of secondary accelerating contactors in accordance with Tables 9 and 29, with automatic timing means for each contactor.

The panel as described above includes protection. If a panel is used with a crane protective panel, the following are omitted:

- One line switch.
- One overload relay.
- One undervoltage relay.



CONTACTOR SEQUENCE TABLE												
MASTER HANDLE POSITION		REVERSE					OFF	FORWARD				
		5	4	3	2	1		1	2	3	4	5
CONTACTORS	F							X	X	X	X	X
	R	X	X	X	X	X						
	1A	X	X	X	X				X	X	X	X
	2A	X	X	X						X	X	X
	3A	X	X								X	X
	4A 8 5A	X										X
	X- INDICATES CONTACTORS CLOSED											

CONTACTOR NOMENCLATURE		
F	FORWARD	MECHANICALLY INTERLOCKED
R	REVERSE	
1A	PLUGGING	
2A	ACCELERATING	
3A		
4A		
5A		

RELAYS				
NOMENCLATURE		GAP	SETTING	
2AR	ACCELERATING	1/8"	0.50	SEC. TO RELEASE
3AR		1/8"	1.25	
4AR		1/8"	1.00	
5AR		1/8"	0.75	
OL	OVERLOAD (AUTOMATIC RESET)	250% RATED PRIMARY AMPERES		
PR	PLUGGING	85% RATED PRIMARY AMPERES		
UV	UNDERVOLTAGE			

FIG. 342. Elementary connections of reversing plugging a-c crane controller.

With the controller as shown in Fig. 342, symmetrical operation is obtained in both directions of rotation. The closing of secondary accelerating contactors is controlled by definite time drop-out d-c accelerating relays, the coils of which are energized from the a-c control source through a metallic rectifier. A control transformer is used for the rectifier circuit at control voltages above 220, in order to obtain a more economical rectifier. Limit switches for overtravel protection are connected in series with the coils of the reversing contactors. A Thrustor brake is shown connected to the primary terminals of the motor. On machinery where a heavy mass is moved, gradually setting brakes are advantageous as they bring about smooth stopping. When quicker brake setting is desired solenoid brakes are used.

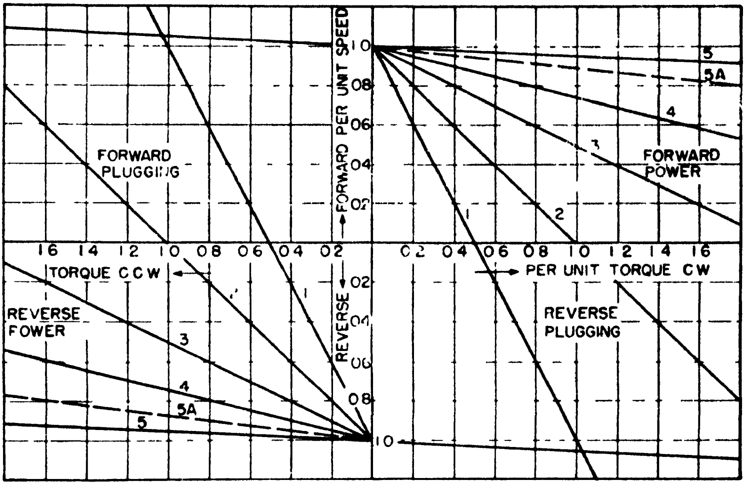


FIG. 343. Speed-torque curves of reversing plugging a-c crane controller.

Electric braking is accomplished by plugging. The counter torque of the motor is utilized to bring the drive to a dead stop by electric braking or to effect rapid reversal. A current limit type plugging relay *PR* prevents the closing of plugging contactor 1*A* and subsequent accelerating contactors until the motor current has dropped to a low value, indicating that the motor has decelerated to a low speed. In Fig. 343 the speed-torque curves are plotted which are obtained on the various master switch positions. The total resistance contained in the resistor, plus internal rotor resistance, is twice normal ohms; thus the starting torque on the first master switch position is one half normal torque. The initial plugging torque obtained with such a re-

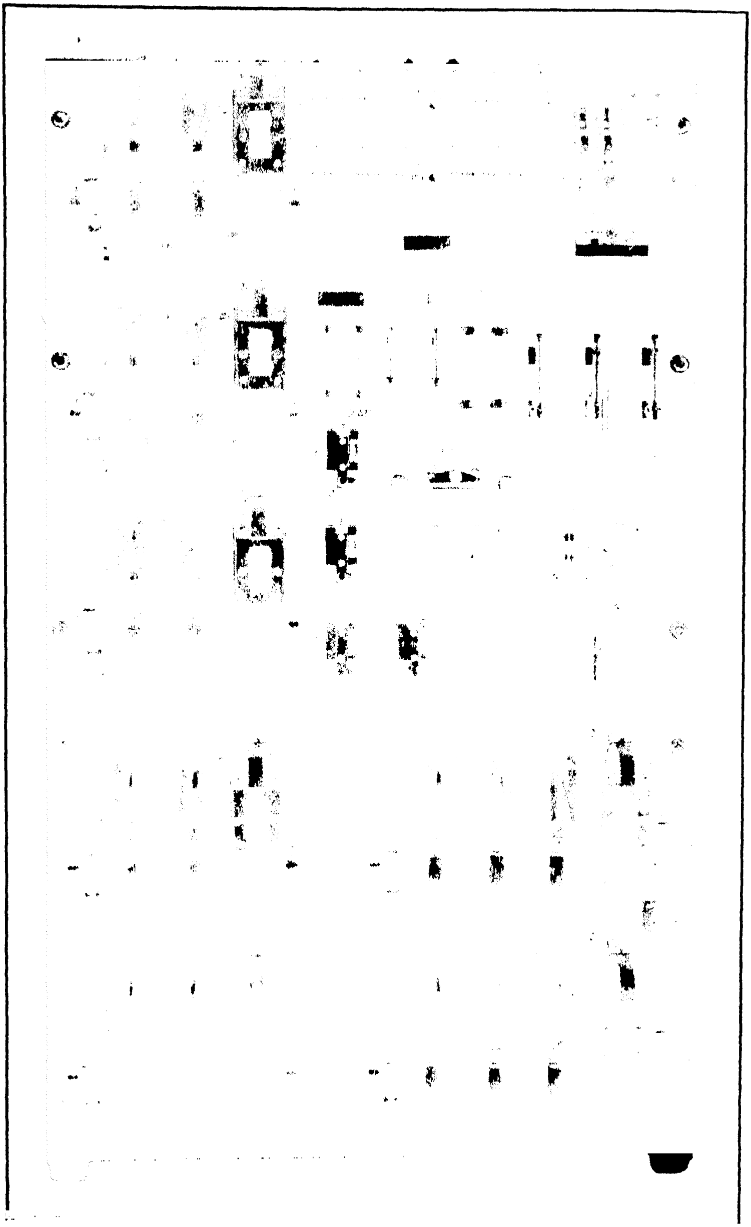


FIG. 344. Open type reversing plugging a-c crane control panel.

sistor lay-out is approximately equal to normal torque. Resistors for light-duty cranes are NEMA class 152, whereas on heavy-duty cranes class 162 is used.

Reversing controllers with plugging are used primarily on crane bridge and trolley drives. Reversing controllers are also used on hoists equipped with mechanical load brakes so that the motor has to deliver power to the load both during hoisting and lowering. Hoist controllers are like the travel controller just described, except that plugging is not required. The plugging relay is omitted. Plugging contactor 1A is used as a low-torque contactor. The resistor lay-out is the same as for a plugging controller, the low starting torque on the first master switch position being used for maneuvering a light load or an empty hook. Speed-torque curves (Fig. 343) apply to reversing drives, regardless of whether plugging is used or not.

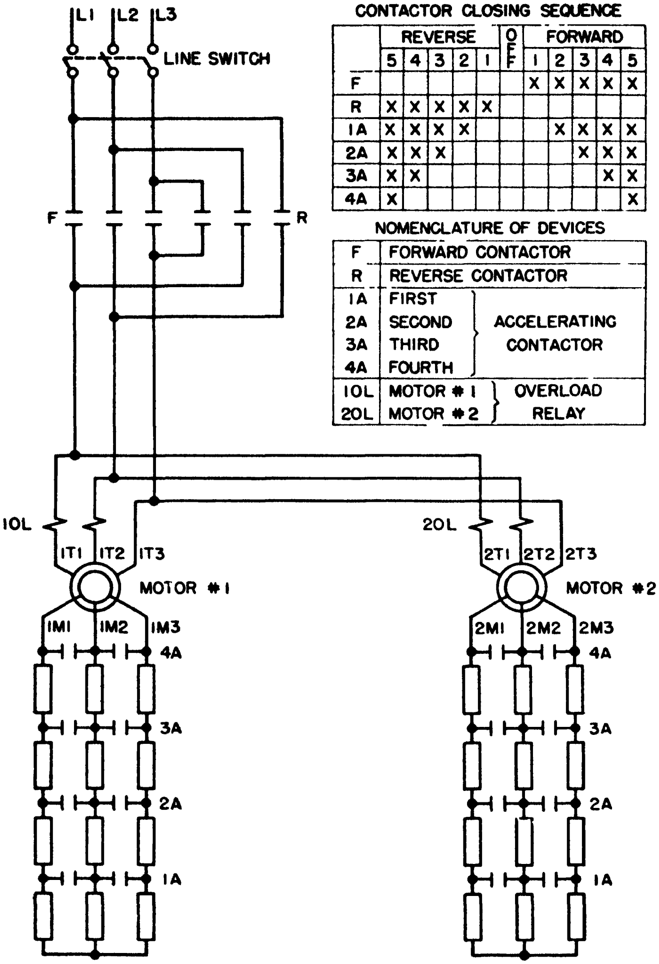
A typical reversing plugging a-c crane control panel of open construction is shown in Fig. 344.

Duplex Controllers

When two motors are geared to the same drive, and they are controlled simultaneously from one master switch, a single duplex control panel is used. Figure 345 is an elementary power diagram of a duplex reversing controller. The stators of both motors are connected to the power supply through a common pair of reversing contactors. Each motor is protected individually by its own overload relay. On the diagram shown, a common line switch is used, assuming that in case of failure of one motor it is not desired to maintain emergency operation with a single motor. Single-motor operation could be provided by connecting an individual line switch in each motor primary circuit.

The secondary circuits of both motors are electrically separated, and each motor has its own resistor to avoid the possibility of circulating current flowing between the two motors. However, a single set of four-pole accelerating contactors short-circuit corresponding sections of both resistors. Control panel space is reduced, as compared with a panel mounting two separate sets of contactors. Also the use of four-pole accelerating contactors insures that resistance sections are short-circuited simultaneously in the two motor secondaries, resulting in smooth acceleration.

Any of the conventional methods of controlling accelerating contactor closing sequence may be used. With definite time control of acceleration, there is no connection between power circuits and accelerating relays. If single-motor operation is desired, the faulty motor is disconnected and no changes are required in the control circuits. If current limit relays or rotor frequency relays are used, such



CONTACTOR CLOSING SEQUENCE

	REVERSE					OFF	FORWARD				
	5	4	3	2	1		1	2	3	4	5
F							X	X	X	X	X
R	X	X	X	X	X						
1A	X	X	X	X				X	X	X	X
2A	X	X	X						X	X	X
3A	X	X								X	X
4A	X										X

NOMENCLATURE OF DEVICES

F	FORWARD CONTACTOR	
R	REVERSE CONTACTOR	
1A	FIRST	ACCELERATING CONTACTOR
2A	SECOND	
3A	THIRD	
4A	FOURTH	
1OL	MOTOR # 1	OVERLOAD RELAY
2OL	MOTOR # 2	

FIG. 345. Power circuits of a-c reversing duplex controller.

relays are connected to one of the two motors, and in case of single-motor operation, a transfer switch is included to connect the relays to either motor circuit.

Hoist Controllers General

A-c induction motors are inherently less flexible in their speed-torque characteristics than d-c motors, particularly when the motor is called upon to deliver dynamic braking torque to retard overhauling loads. When an induction motor is driven as a generator by an overhauling load in the same direction of rotation as its flux, the motor can develop a retarding torque only at speeds above synchronous, and in that range speed control is possible by varying resistance connected in the rotor circuit. Below synchronous speed, no speed control is possible except with counter torque obtained by plugging. To obtain more desirable braking torque characteristics at speeds below synchronous, apparatus extraneous to the motor is necessary.

When induction motors were first applied to hoists, they were used on balanced hoists, particularly mine hoists, where a loaded skip is hoisted while an empty skip is lowered, requiring the motor to deliver driving torque in both directions of rotation. Unbalanced hoists, particularly crane hoists, used the motor only for hoisting, and loads were lowered under the control of mechanical brakes, with the motor disconnected from the line. Mechanical load brakes were then introduced which restrain the load in the lowering direction and require power from the motor to drive the load down. Mechanical complications and high maintenance are undesirable features of mechanical load brakes so that they are used only on miscellaneous-duty and infrequently operated cranes.

For many years, d-c motors were used almost exclusively on cranes requiring accurate spotting of the load, and series motors are still unsurpassed as far as simplicity and flexibility of control is concerned. In areas where large blocks of d-c power are available, such as in steel mills, d-c motors are preferred. Cranes which are remote from power sources and carry their own gasoline or Diesel power plant are generally equipped with d-c drives. The advent of large interconnected a-c power systems for industrial plants, providing low-cost a-c power almost everywhere, has given an impetus to the development of a-c hoist control systems. From an economic point of view the use of a-c motors for crane work is desirable since conversion equipment, higher d-c distribution system costs, and the additional losses of d-c systems can be saved.

Depending on the accuracy with which a load has to be handled and the flexibility required of the hoist controller, cranes can be classified as follows:

A. Cranes handling material in bulk, such as grab bucket cranes, cableways, coal and ore bridges. The load varies between definite limits, the maximum load being determined by the dimensions of the bucket and the specific weight of the material handled, and the minimum load being an empty bucket. Accurate inching is not required. A low-torque point is necessary to pay out cable with the bucket resting on the pile in order to maneuver the bucket.

B. Cranes handling miscellaneous work. The load varies over a wide range. In this category fall shop cranes, power house cranes, shipyard cranes. Accurate spotting of loads is necessary, and control of lowering speeds below synchronous is essential. It is desirable to keep changes of speed with variations in load on any master switch position to a minimum.

The following control systems are available to meet the requirements of a-c crane hoists applications:

1. Plugging or counter torque.
2. Thrustor load brake.
3. Single-phase stator connection.
4. Unbalanced stator connection.
5. D-c dynamic braking.

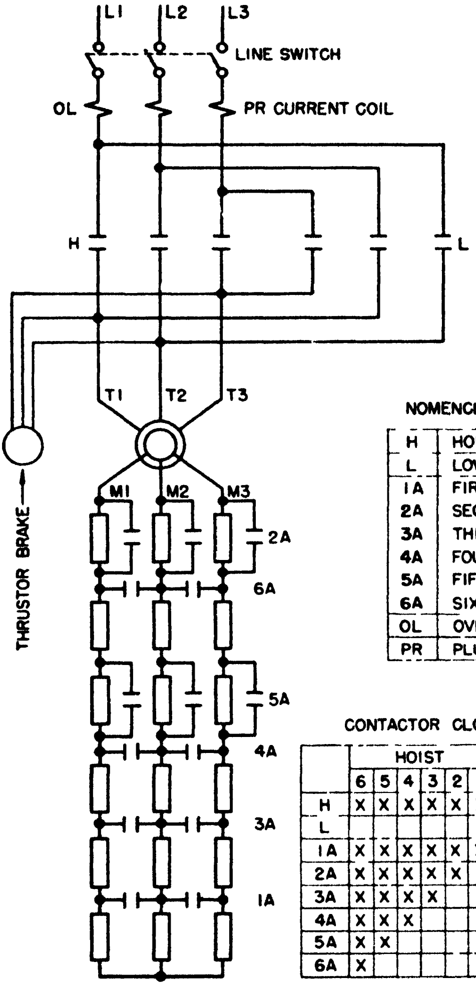
Graduated Plugging Control[1, 2]

The oldest types of a-c hoist controllers, widely used on bulk-handling grab bucket cranes, accomplish control of the load during lowering by connecting the motor primary circuit in the hoisting direction and inserting sufficient resistance in the secondary circuit so that the load torque is greater than the motor torque at standstill. The energy transmitted by the load to the motor is dissipated in the secondary resistor. Speed control is obtained by varying the amount of secondary resistance. As several master switch positions are available to control the amount of plugging or counter torque developed by the motor, such controllers are called graduated plugging controllers.

Figure 346 is an elementary power diagram of a graduated plugging crane hoist controller. The speed-torque curves obtained on the various master switch positions are plotted in Fig. 347. A six-point controller is shown, but the number of master switch positions may be varied by using a different number of secondary contactors, depending on the size of the hoist and the accuracy of lowering control desired.

In the hoisting direction, contactor *H* connects the motor primary to the line with correct phase sequence. Secondary contactors are closed in sequence on the various master switch positions. Accelerating relays, such as definite time, current limit, or frequency relays, govern the interval between contactors, independent of the speed with which the master switch is manipulated. In the hoisting direction, the controller shown does not differ from a conventional reversing controller.

When the master switch is turned in the lowering direction, nothing happens until the sixth position is reached. The motor primary



NOMENCLATURE OF DEVICES

H	HOIST CONTACTOR	
L	LOWER CONTACTOR	
1A	FIRST	ACCELERATING CONTACTOR
2A	SECOND	
3A	THIRD	
4A	FOURTH	
5A	FIFTH	
6A	SIXTH	
OL	OVERLOAD RELAY	
PR	PLUGGING RELAY	

CONTACTOR CLOSING SEQUENCE

	HOIST						OFF	LOWER					
	6	5	4	3	2	1		1	2	3	4	5	6
H	X	X	X	X	X	X		X	X	X	X	X	
L													X
1A	X	X	X	X	X	X		X	X	X			X
2A	X	X	X	X	X						X		X
3A	X	X	X	X				X	X				X
4A	X	X	X					X					X
5A	X	X						X	X				X
6A	X							X					X

FIG. 346. Power circuits of graduated plugging crane hoist controller.

is connected to the line through contactor *L* with reversed phase rotation, and all accelerating contactors close in sequence. The motor accelerates to its full speed which, with an overhauling load, is slightly above synchronous. The load is lowered at its maximum speed in accordance with curve 6–*L*, a very stable curve, preventing the motor from overspeeding even with a heavy overload. The motor acts as a generator, pumping power back into the line.

To decelerate the load preparatory to stopping, the master switch is moved toward the off position. On the fifth position, contactor *L* opens and contactor *H* closes, connecting the motor primary to the line in the hoisting direction, while the motor still turns in the opposite direction. All accelerating contactors are dropped out, and the motor develops a weak counter torque to retard the load. Turning the master switch step by step to position 1 causes accelerating contactors to close, and the counter torque is gradually increased, thus bringing the load to a stop preparatory to setting the brake in the off position. A current type plugging relay *PR* limits the plugging torque when the master switch is rapidly turned to position 1 by preventing contactors 3*A* to 6*A* from closing and curves 2–*L* and 1–*L* from becoming effective, until after the motor has decelerated to a low speed along curve 3–*L*.

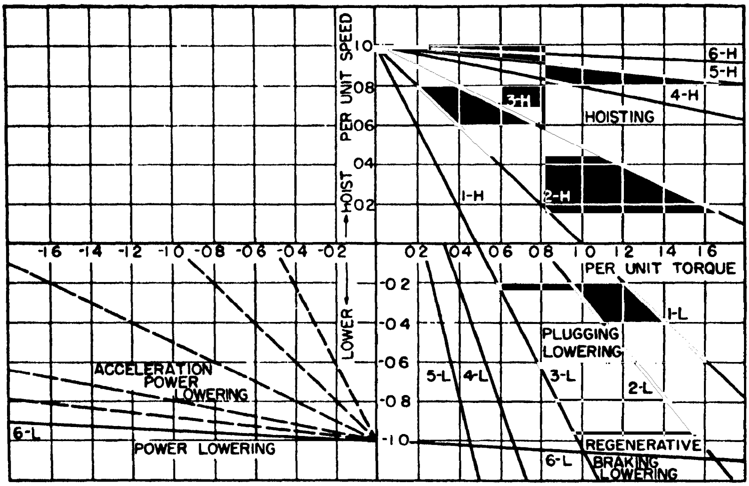


FIG. 347. Speed-torque curves of graduated plugging crane hoist controller.

Care must be taken to prevent setting of the brake during the transition between positions 5 and 6 of the master switch, while contactor *L* drops out and contactor *H* closes. A Thrustor brake, having an inherent time delay in setting, stays released during the slight time interval while the motor is disconnected from the line. When a solenoid brake is used, a separate brake contactor keeps the brake energized during the transition period.

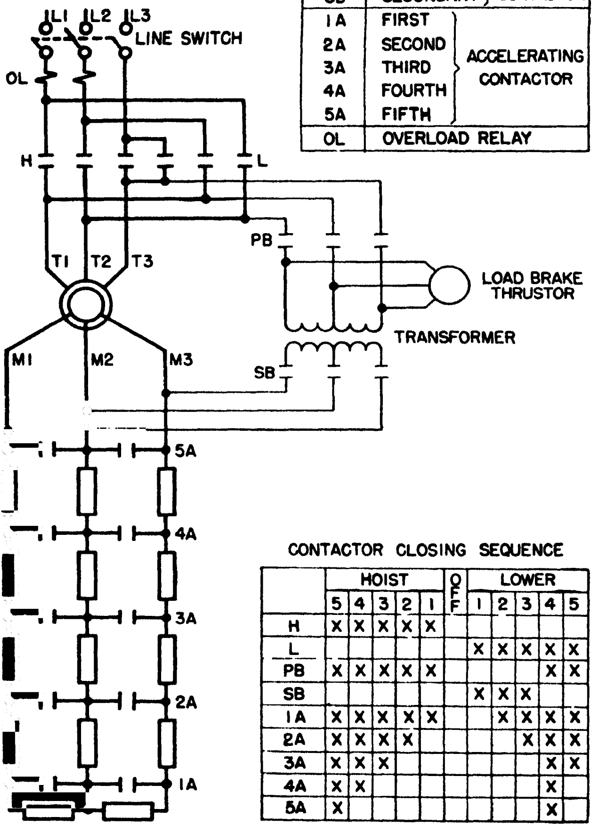
Although plugging obtains lowering speeds between zero and synchronous, it must be recognized that the resultant speed-torque curves are not ideal for all kinds of hoist applications. The curves are steep, a small variation in load corresponding to a large variation in speed. Overloads may cause overspeeding of the motor, and the operator must exercise care in manipulating the master switch. Additional safety devices, responding to motor speed, are sometimes employed. Plugging control is well suited for bucket hoists which do not require accurate speed control and on which overloads are not encountered. Accurate maneuvering of loads, as required on power house or shipyard cranes, is difficult with plugging control, and this type of control is not recommended for such applications. Wherever graduated plugging control is able to meet operating requirements, it offers the advantage of simplicity. It is the least expensive and easiest to maintain type of hoist control, as it requires a minimum amount of electrical equipment.

Lowering Control with Thrustor Load Brake

Since the basic disadvantage of lowering by counter torque is the steepness of the speed-torque curves, other systems of a-c hoist control aim at providing lowering curves between standstill and synchronous speed, which are considerably flatter, thus obtaining less variation of speed with variations in load on any master switch position.

Thrustor brakes can be used as load brakes, applying a retarding torque which varies with motor speed. Refer to Fig. 348, which is an elementary power diagram of a crane hoist controller with Thrustor load brake. The motor primary is connected to the line through a pair of reversing contactors. A resistor in the motor secondary circuit is short-circuited in steps by accelerating contactors. Thus the motor power circuit does not differ from that of a conventional reversing controller. The only detail which is special is the resistor lay-out. The first resistor division, which is short-circuited by contactor 1*A*, contains a large amount of resistance, more than ten times normal. This resistor division is ineffective during hoisting, and it is used only during lowering.

The load brake Thrustor is de-energized in the off position of the master switch, causing the brake to set. When the master switch is turned to any of the running positions, the brake Thrustor is energized by the closing of either one of two brake contactors. Through contactor *PB*, the Thrustor is connected to the line, and the brake is fully released like any conventional brake. When contactor *SB* closes, the Thrustor is connected to the motor secondary circuit, and it is thus connected to a power source, the voltage and frequency of which vary as a function of motor speed.



NOMENCLATURE OF DEVICES

H	HOIST CONTACTOR	
L	LOWER CONTACTOR	
PB	PRIMARY	BRAKE CONTACTOR
SB	SECONDARY	
1A	FIRST	ACCELERATING CONTACTOR
2A	SECOND	
3A	THIRD	
4A	FOURTH	
5A	FIFTH	
OL	OVERLOAD RELAY	

CONTACTOR CLOSING SEQUENCE

	HOIST					OFF	LOWER				
	5	4	3	2	1		1	2	3	4	5
H	X	X	X	X	X						
L							X	X	X	X	X
PB	X	X	X	X	X					X	X
SB							X	X	X		
1A	X	X	X	X	X			X	X	X	X
2A	X	X	X	X					X	X	X
3A	X	X	X							X	X
4A	X	X								X	
5A	X									X	

FIG. 348. Power circuits of crane hoist controller with Thrustor load brake.

When the hoist motor is at standstill, the secondary frequency is equal to line frequency, and the secondary voltage is equal to line voltage, multiplied by the turn ratio of the motor primary and secondary windings. A transformer, connected between contactor *SB* and the Thrustor, has an equal turn ratio. When *SB* is closed and the hoist motor primary is energized at standstill, rated voltage at line frequency is impressed on the Thrustor motor, which thus turns at its normal speed and causes the brake to release fully. As the hoist motor accelerates, its secondary voltage and frequency decrease proportional to the slip. The Thrustor motor speed decreases at the same rate. The thrust delivered by the impeller of the Thrustor decreases at a still faster rate. When the hoist motor speed increases to approximately 0.14 of synchronous, the thrust is no longer high enough to overcome the tension of the brake spring, and the brake shoes begin to rub on the brake wheel. With increasing hoist motor speed, the Thrustor motor speed decreases further, and the brake sets partially, the amount of braking torque delivered by the load brake increasing with increasing hoist motor speed, until a balance is established between the brake torque and the load torque plus the hoist motor torque.

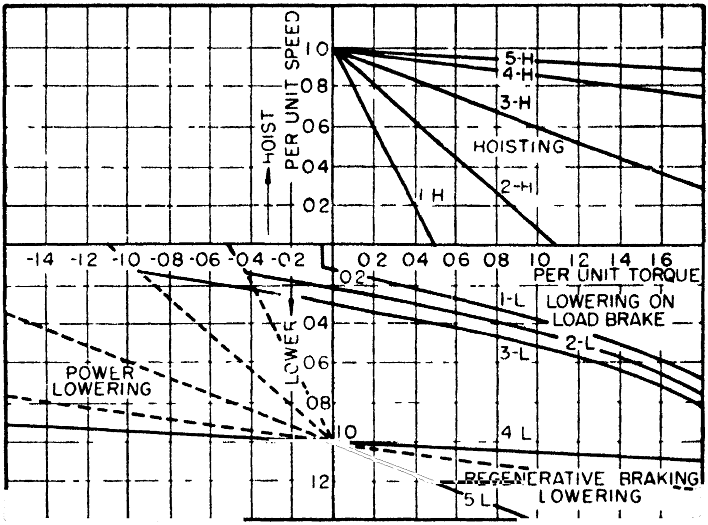


Fig. 349. Speed-torque curves of crane hoist controller with Thrustor load brake.

Speed-torque curves obtained with a hoist controller with Thrustor load brake are plotted in Fig. 349. Turning the master switch in the lowering direction to the first position causes contactors *L* and *SB* to close. The motor primary is connected to the line with such a phase sequence that torque is developed to drive down the load. All available resistance is inserted in the motor secondary circuit, and the torque delivered by the motor is a very small fraction of normal motor torque. At standstill, the Thrustor brake is fully released, but as the hoist motor accelerates, the load brake sets partially, and acceleration takes place along curve 1–*L*, the ultimate speed depending on the load. In the second master switch position, contactor 1*A* closes, which increases the power torque delivered by the hoist motor in the lowering direction. With a given load, the hoist motor must accelerate to a higher speed before the load brake torque equals the sum of the load torque and the motor torque, as indicated by curve 2–*L*. In the third master switch position, contactor 2*A* closes, the motor torque is increased, and curve 3–*L* obtains somewhat higher lowering speeds. In the fourth master switch position, contactor *SB* opens and *PB* closes, connecting the Thrustor to the line and causing the load brake to release fully. Accelerating contactors 3*A*, 4*A*, 5*A* close in sequence, and the hoist motor accelerates to a speed slightly above synchronous, the motor holding the load at a steady speed by regenerative braking. On this master switch position, motor operation is the same as on any conventional reversing controller.

On many reversing controllers, the fourth is the last master switch position. In Fig. 349 a method is indicated by which still higher lowering speeds can be obtained with a fifth master switch position. By dropping out accelerating contactors 4*A* and 5*A* and thus inserting resistance in the hoist motor secondary circuit, higher lowering speeds above synchronous can be obtained, as indicated by curve 5–*L*. This is a connection which has nothing to do with the load brake but can be used on any controller utilizing regenerative braking. In selecting the amount of resistance connected in the motor secondary circuit, care must be taken to limit the resistance to a value which will prevent the motor from exceeding its maximum safe speed with the highest load expected to be handled on the crane hook. Although this connection permits lowering heavy loads at higher speeds, no gain in speed is obtained during lowering of a light hook, when increased speed would be most desirable.

As compared with a graduated plugging controller, the load brake lowering curves 1–*L*, 2–*L*, and 3–*L* provide more stable speeds. and loads can be spotted more accurately. A disadvantage is that the speed-torque curves corresponding to three master switch positions are close together, and the speed range between standstill and full speed is not divided evenly between master switch positions. In designing the load brake, it must be taken into account that the rubbing between shoes and wheel, when the brake is partially released, generates heat which must be dissipated by the wheel. The specific pressure between lining and wheel should be low, to keep the wear of the brake lining at a minimum.

Single-Phase Lowering Control

Dynamic braking at subsynchronous speeds is possible by applying single-phase excitation to the stator and inserting resistance in the secondary circuit. It is a special case of applying an unbalanced primary voltage, positive and negative sequence voltages being of equal magnitude. The motor can be visualized as consisting of two motors superimposed, one motor developing positive sequence torque the other motor developing negative sequence torque, the net torque at the motor shaft being the net difference between the two torques.

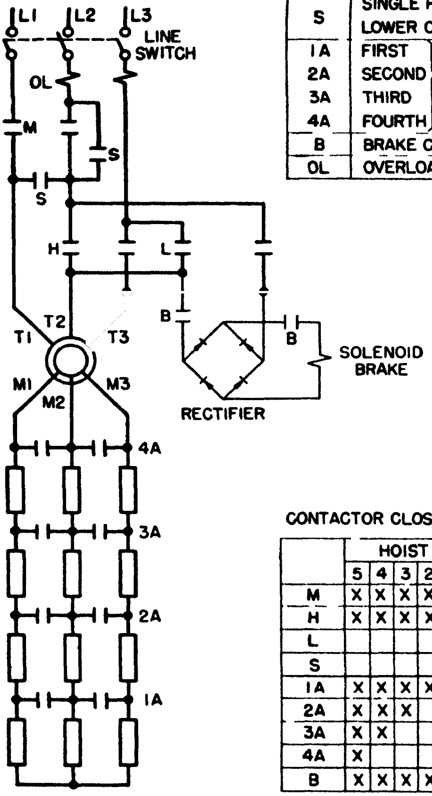
In a hoist motor, positive sequence torque is in the direction to hoist the load, thus restraining an overhauling load. In other words, positive sequence torque is equivalent to counter torque. Negative sequence torque is in the direction to drive the load in the lowering direction. At standstill, the positive and negative sequence torques are equal, and the net torque is zero, so that an induction motor with single-phase voltage applied to the stator cannot develop a starting torque. An overhauling load is required to accelerate the motor in the lowering direction. As the speed increases, the negative sequence torque decreases and the positive sequence torque increases. When synchronous speed is reached, the negative sequence torque is zero and only the positive sequence torque appears as a net dynamic braking torque. Thus the speed-torque curve, with a large amount of resistance in the secondary, is substantially a straight line through the origin, the slope of which depends on the amount of resistance in the secondary circuit.

The Electric Controller and Manufacturing Company has developed a system of a-c hoist control employing a single-phase lowering connection. Figure 350 is an elementary diagram of the power circuits, and in Fig. 351 the resultant speed-torque curves are plotted for various master switch positions. In the hoisting direction, contactor closing sequence is the same as for a conventional reversing controller, and the closing of the accelerating contactors is controlled by frequency relays connected to the hoist motor secondary circuit. The solenoid brake is equipped with a d-c coil which is energized from the motor primary circuit through a rectifier. To obtain quick brake setting, the brake contactor interrupts both the a-c and the d-c leads of the rectifier, when the master switch is returned to the off position.

When the master switch is turned to the first position lower, contactors *L* and *S* close, while *M* stays open. Motor primary terminals *T*1 and *T*3 are tied together and connected to line phase *L*2, whereas motor primary terminal *T*2 is connected to line phase *L*3. Single-phase voltage is applied to the motor primary winding, and contactor 1A closes, leaving approximately normal ohms in the motor secondary

NOMENCLATURE OF DEVICES

M	LINE CONTACTOR
H	HOIST CONTACTOR
L	LOWER CONTACTOR
S	SINGLE PHASE LOWER CONTACTOR
1A	FIRST ACCELERATING CONTACTOR
2A	SECOND ACCELERATING CONTACTOR
3A	THIRD ACCELERATING CONTACTOR
4A	FOURTH ACCELERATING CONTACTOR
B	BRAKE CONTACTOR
OL	OVERLOAD RELAY



CONTACTOR CLOSING SEQUENCE

	HOIST					OFF	LOWER		
	5	4	3	2	1		1	2	3
M	X	X	X	X	X			X	X
H	X	X	X	X	X				
L							X	X	X
S							X		
1A	X	X	X	X			X		X
2A	X	X	X					⊗	X
3A	X	X						⊗	X
4A	X							⊗	X
B	X	X	X	X	X		X	X	X

⊗ INDICATES THAT CONTACTORS CLOSE UNDER CONTROL OF FREQUENCY RELAYS IF LOAD CAUSES MOTOR TO OVERSPEED

FIG. 350. Power circuits of crane hoist controller with single-phase lowering (Courtesy The Electric Controller & Manufacturing Co.)

circuit. Performance is along curve 1–L and full load is lowered at approximately 0.7 full-load hoisting speed.

Turning the master switch to the second position lower causes contactors S and 1A to open and M to close. The motor primary is then connected to the line with symmetrical three-phase voltage applied and with approximately twice normal ohms connected in the secondary circuit. The motor develops a limited power torque in the lowering direction in accordance with curve 2–*L*. This master switch position is intended to be used for driving down a light load or an empty hook, which would not overhaul the motor. If this master switch position were used to lower a heavy load, overspeeding of the hoist motor would result. To avoid this danger, frequency relays cause accelerating contactors to close and short-circuit the secondary resistor, if the motor should accelerate above synchronous speed.

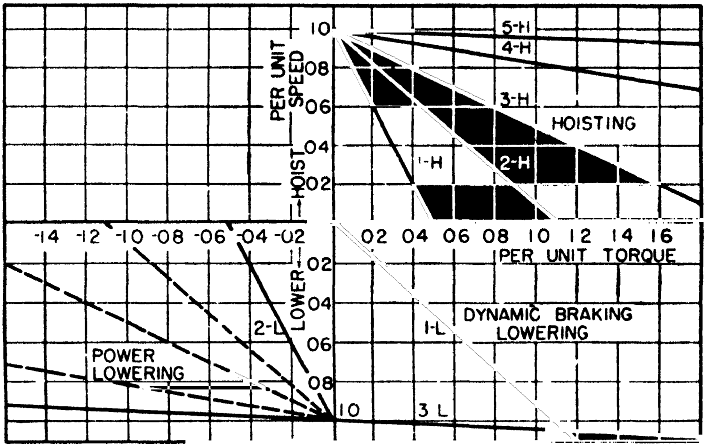


FIG. 351. Speed-torque curves of crane hoist controller with single-phase lowering. (Courtesy The Electric Controller & Manufacturing Co.)

In the third master switch position, all accelerating contactors close in sequence, under the control of frequency relays. Automatic acceleration is indicated by the broken curves in the power-lowering quadrant. With overhauling loads, regenerative braking takes place in accordance with curve 3–*L*.

Single-phase lowering is accompanied by greater heating of the motor than during balanced voltage operation. Motor heating is proportional to the sum of positive and negative sequence torque, and while lowering full load, motor heating is approximately twice the heating encountered when hoisting full load. Thus the first master switch position should not be used to lower the load through its full travel. The proper way of operating a single-phase lowering controller is to advance the master switch to the second or third position and to lower at full speed. As the end of the lowering travel is approached, the master switch is returned to the first position. This decelerates the load to a subsynchronous speed, preparatory to stopping by returning the master switch to the off position and setting the brake.

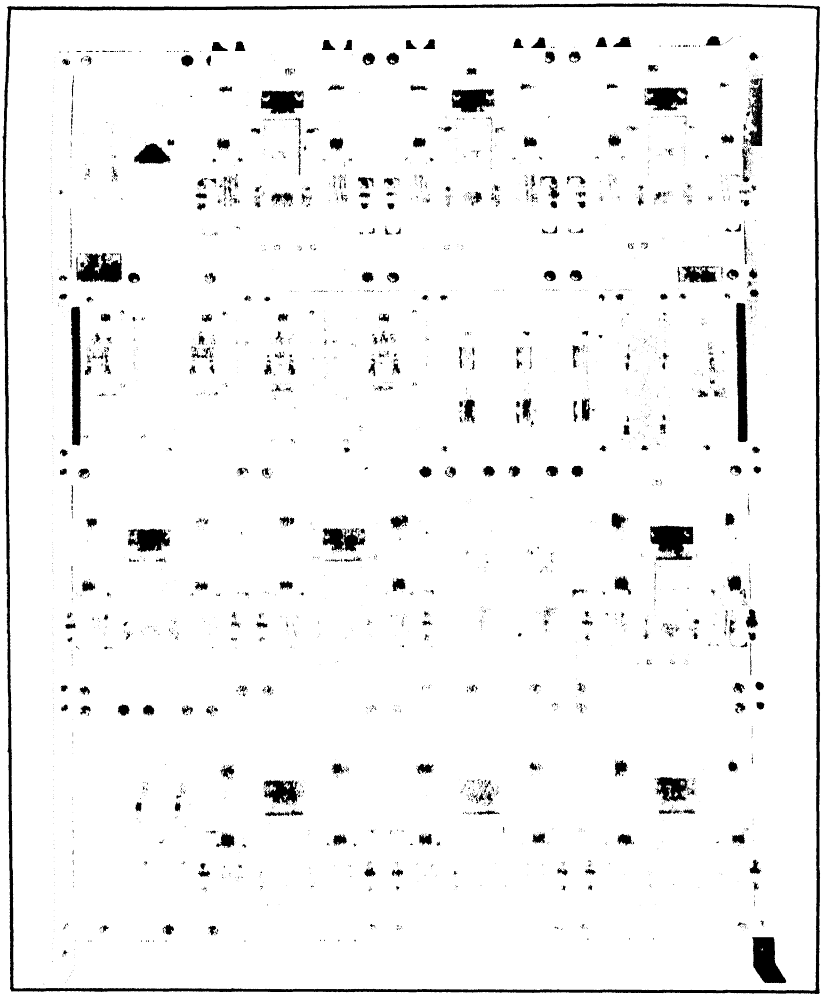
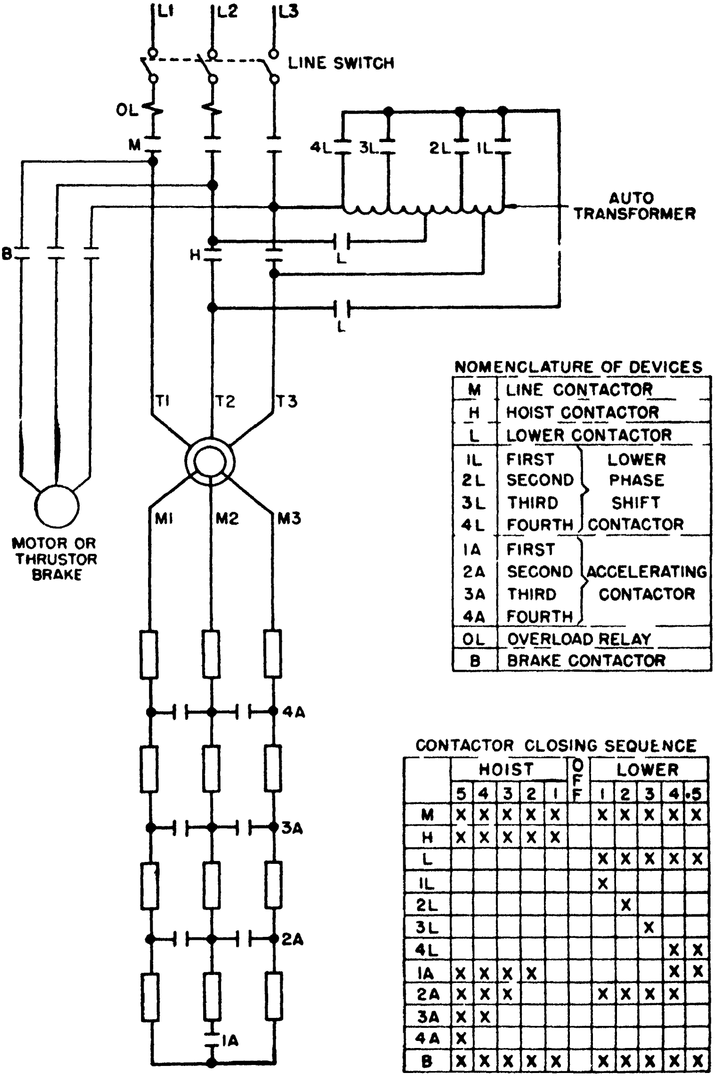


FIG. 352. Open type unit base a-c crane hoist control panel with single-phase lowering. (Courtesy The Electric Controller & Manufacturing Co.)

Shown in Fig. 352 is an a-c crane hoist control panel with unit base construction. It incorporates single-phase lowering and frequency relays for controlling contactor sequence.

Hoist Control with Unbalanced Stator Voltage

In Chapter 3 it has been explained that with unbalanced polyphase voltage applied to the primary, the speed-torque curves of an induction motor are quite different from the ones obtained with balanced



NOMENCLATURE OF DEVICES

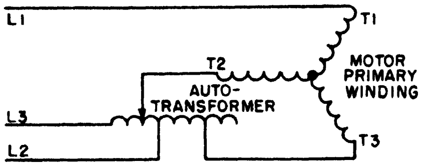
M	LINE CONTACTOR	
H	HOIST CONTACTOR	
L	LOWER CONTACTOR	
1L	FIRST	LOWER PHASE SHIFT CONTACTOR
2L	SECOND	
3L	THIRD	
4L	FOURTH	
1A	FIRST	ACCELERATING CONTACTOR
2A	SECOND	
3A	THIRD	
4A	FOURTH	
OL	OVERLOAD RELAY	
B	BRAKE CONTACTOR	

CONTACTOR CLOSING SEQUENCE

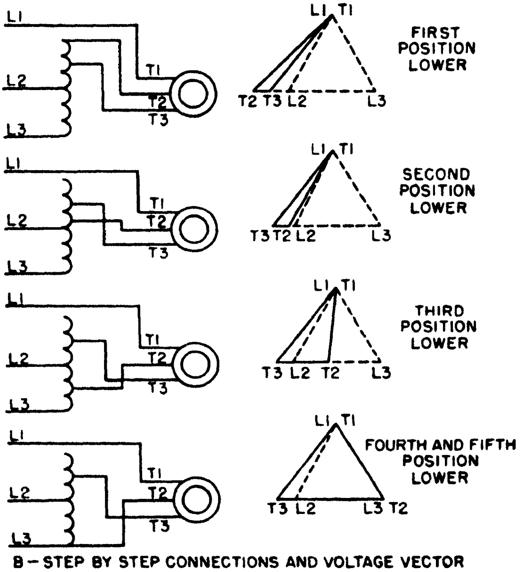
	HOIST					OFF	LOWER				
	5	4	3	2	1		1	2	3	4	5
M	X	X	X	X	X		X	X	X	X	X
H	X	X	X	X	X						
L							X	X	X	X	X
1L							X				
2L								X			
3L									X		
4L										X	X
1A	X	X	X	X						X	X
2A	X	X	X				X	X	X	X	
3A	X	X									
4A	X										
B	X	X	X	X	X		X	X	X	X	X

Fig 353 Power circuits of crane hoist controller with unbalanced primary connections (Courtesy Cutler-Hammer Inc)

primary voltage. Particular reference is had to Fig. 82, indicating how performance curves can be constructed for unbalanced primary voltages containing various amounts of positive and negative sequence voltage. By proper selection of primary voltage conditions, dynamic braking can be obtained at speeds below synchronous.



A–SIMPLIFIED SKETCH OF TRANSFORMER AND MOTOR PRIMARY CONNECTIONS



B–STEP BY STEP CONNECTIONS AND VOLTAGE VECTOR DIAGRAMS

FIG. 354. Details of unbalanced stator lowering connections.

One form of a-c crane hoist controller, using unbalanced primary voltage, has been developed by Cutler-Hammer, Inc.[3] Figure 353 is an elementary diagram of the power circuits. Hoisting connections are conventional, with balanced voltage applied to the stator terminals and speed control by short-circuiting secondary resistor sections. To reduce the amount of resistance required to obtain a low starting torque on the first master switch position, one secondary phase is left open. Closing of contactor 1A on subsequent master switch positions balances the three secondary phases.

When the master switch is turned to the lowering positions, an autotransformer is connected to the line phases *L*2 and *L*3. Stator terminal *T*3 is connected to a fixed tap on an overhung section of the transformer winding. Stator terminal *T*2 is connected to various taps on the transformer winding, depending on the master switch position. In Fig. 354 the stator connections are shown in a simplified manner for each master switch position, together with the corresponding voltage vector diagrams. The balanced line voltage triangle is indicated by broken lines. The solid lines represent the voltage triangles applied to the motor primary terminals. These voltages are quite unbalanced, containing various amounts of positive and negative sequence voltage. In master switch positions 1 to 4, the amount of secondary resistance is fixed and the amount of voltage unbalance is varied. In the fifth master switch position additional resistance is inserted in the secondary circuit.

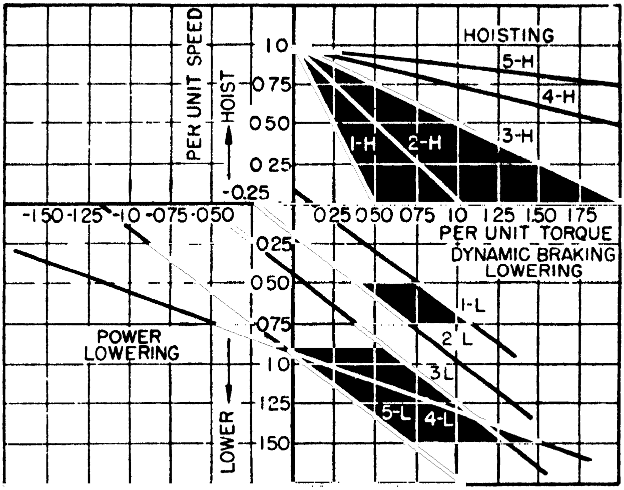


FIG. 355 Speed-torque curves of crane hoist controller with unbalanced primary connections. (Courtesy Cutler-Hammer, Inc.)

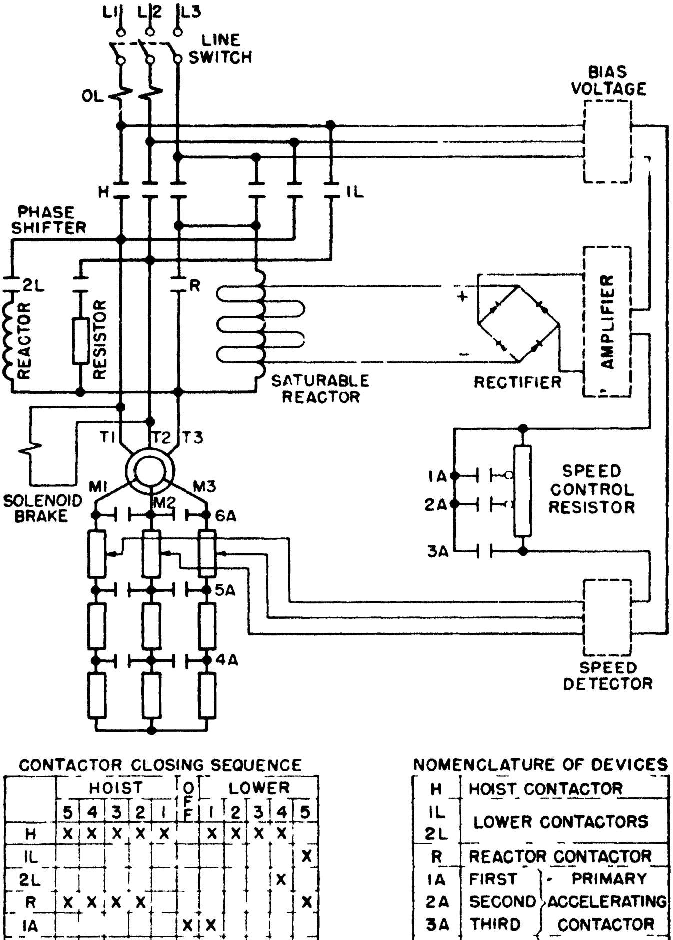
The speed-torque curves are plotted in Fig. 355. Lowering speeds below and above synchronous are obtained with overhauling loads. The slope of the curves, that is, the variation of speed with torque, is considerably less than with a plugging controller, although the curves are not so flat as those obtainable with d-c hoist controllers. The first lowering curve is similar to the ones obtained with a Thrustor load brake or with a single-phase excitation, and subsequent curves are well spaced apart. Power torque for lowering an empty hook is available on master switch positions 2 to 5.

The control system just described employs a fixed amount of voltage unbalance on each master switch position. Another control system, developed by Westinghouse Electric Corporation,[4, 5] introduces an unbalance, the amount of which varies with motor speed. The power circuits are shown in Fig. 356. Unbalancing the motor primary voltage is effected by a saturable reactor, connected in series with one stator phase, and a phase shifter network, consisting of a resistor and a reactor, connected across all three phases between the line and the stator terminals.

The saturable reactor contains two windings on a common core. The main winding is connected in the a-c circuit to the motor. A control winding is d-c excited and provides a d-c flux, over which the a-c flux is superimposed. Depending on the amount of d-c excitation, the reactor core is saturated to a variable extent. Thus its reactance at line frequency varies as a function of the excitation of the d-c coil. Connecting this variable reactance in one of the motor stator phases produces a variable unbalance of the voltage applied to the motor primary terminals.

A metallic rectifier provides d-c excitation for the saturable reactor. Three control networks containing rectifiers, transformers, and capacitors are used to control the magnitude of the d-c excitation. The speed detector measures motor secondary voltage and produces a signal inversely proportional to motor speed. This signal is balanced against a bias voltage obtained from line voltage. A static amplifier feeds the difference between bias voltage and speed signal into the rectifier supplying the saturable reactor excitation. A potentiometer resistor, forming part of the amplifier circuit, is used to adjust the level of d-c excitation as a function of master switch position. In Fig. 356 contactors 1*A*, 2*A*, 3*A* are shown controlling this resistor, but because of the small amount of power required for that control circuit, master switch contacts are generally used directly to short-circuit resistor sections.

The details of the control circuits are quite complicated. A description and complete diagram as well as an analysis of the voltage unbalance obtained can be found in the Wickerham paper.[4] Contrary to the Cutler-Hammer system, the amount of unbalance, that is, the relationship between positive and negative sequence voltage, is not constant on the various master switch positions but varies with load and speed. Thus the speed-torque curves cease to be straight lines. Voltage unbalancing is used not only in the lowering but also in the hoisting direction for the purpose of obtaining light-load hoisting speeds well below synchronous.



CONTACTOR CLOSING SEQUENCE

	HOIST					OFF	LOWER				
	5	4	3	2	1		1	2	3	4	5
H	X	X	X	X	X		X	X	X	X	
1L											X
2L										X	
R	X	X	X	X							X
1A						X	X				
2A						X	X	X			
3A	X	X	X	X		X	X	X	X		
4A	X	X	X								X
5A	X	X									X
6A	X										X

NOMENCLATURE OF DEVICES

H	HOIST CONTACTOR	
1L 2L	LOWER CONTACTORS	
R	REACTOR CONTACTOR	
1A	FIRST	PRIMARY ACCELERATING CONTACTOR
2A	SECOND	
3A	THIRD	
4A	FOURTH	SECONDARY ACCELERATING CONTACTOR
5A	FIFTH	
6A	SIXTH	
OL	OVERLOAD RELAY	

FIG. 356. Power circuits of crane hoist controller with variable primary reactor. (Courtesy Westinghouse Electric Corp.)

Speed-torque curves obtained on the various master switch positions are plotted in Fig. 357. In the first master switch position hoisting, the motor is connected to the line with the reactor in the circuit. Curve 1–*H* indicates that a starting torque of 0.6 and a no-load speed of approximately 0.9 are obtained. This master switch position can be used for maneuvering an empty hook. On the second to fifth master switch positions, the reactor is short-circuited, and balanced voltage is applied to the motor primary. Conventional acceleration is obtained, speed being controlled by the closing of secondary accelerating contactors.

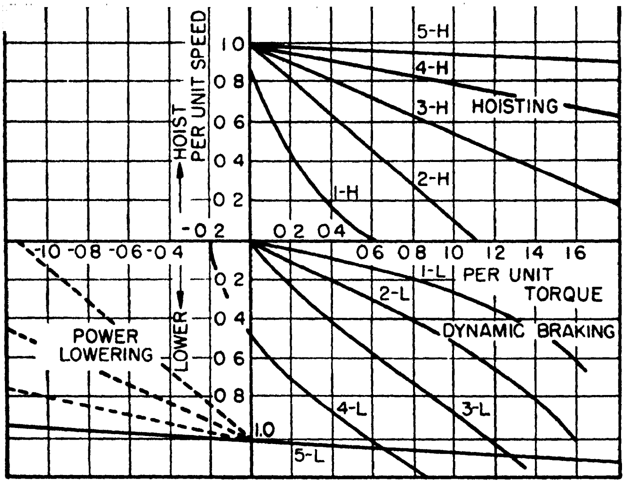


Fig. 357. Speed-torque curves of crane hoist controller with variable primary reactor. (Courtesy Westinghouse Electric Corp.)

In the lowering direction, the motor primary voltage is unbalanced. Positive sequence voltage is supplied from the line as long as contactor *H* is closed. The reactor is connected in the circuit, and its reactance is varied by shifting taps on the speed control resistor in the amplifier circuit. In the first three master switch positions, dynamic braking speed-torque curves are obtained which converge in the origin. Thus dynamic braking torque is available to lower overhauling loads, but no power lowering of a light hook is possible. The lowering curves are quite stable and spaced well apart. In the fourth master switch position the phase shifter is connected in the circuit. The resulting speed-torque curve 4–*L* shows that a light hook can be lowered with power, whereas overhauling loads are lowered with dynamic braking. When the master switch is turned to the fifth position, balanced voltage with reversed phase sequence is applied to the motor primary through contactor 1*L*, the phase shifter being disconnected and the reactor short-circuited. Secondary accelerating contactors close in sequence, and regenerative braking takes place in accordance with curve 5–*L*.

Although unbalancing of the motor primary voltage obtains desirable speed-torque curves superior to those obtained with counter torque control when varying loads are to be lowered accurately, a price has to be paid for the improved performance characteristics. This price is increased heating of the motor. Under any unbalanced voltage condition, the net motor torque is equal to the difference of positive and negative sequence torques, whereas the motor losses are proportional to the sum of positive and negative sequence torques. This increase in losses must be considered when selecting a hoist motor for a given duty cycle.

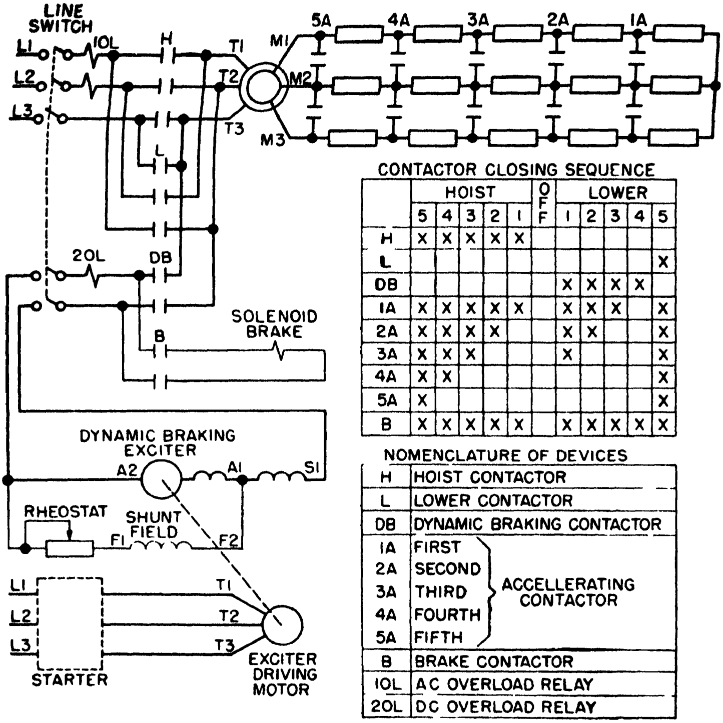
Direct-Current Dynamic Braking[a]

Dynamic braking torque for lowering an overhauling load can be developed by the hoist if its primary is disconnected from the a-c line and excitation is supplied from a source of direct current. Control of the lowering speed can be obtained by varying the amount of resistance connected in the motor secondary circuit.

Figure 358 shows the elementary power circuits of an a-c hoist controller with d-c dynamic braking lowering. A small exciter set is required to furnish d-c excitation. This set consists of a squirrel cage driving motor, connected to the a-c power line through a conventional full-voltage starter, coupled to a flat compound wound d-c generator, the voltage of which can be adjusted by a field rheostat. The exciter set is kept running as long as the hoist is in operation. Once the voltage of the d-c generator has been adjusted so as to obtain the most desirable lowering characteristics it is kept at that setting, and the field rheostat is not touched while the hoist is operated.

In the hoisting direction, the motor primary is connected to the line through contactor *H*. Secondary accelerating contactors close in sequence on the various master switch positions. Definite time, current limit, or speed responsive accelerating relays can be used.

Turning the master switch to the first four positions lowering causes contactor *DB* to close. The motor primary winding is connected to the d-c generator. The further the master switch is advanced, the more resistance is connected in the secondary circuit by dropping out accelerating contactors. The speed-torque curves are plotted in Fig. 359. The dynamic braking lowering curves slope away from the origin at various angles. D-c dynamic braking provides stable lowering of overhauling loads, and the speed is increased by increasing the amount of resistance connected in the secondary circuit. Power lowering of an empty hook is not possible with the d-c dynamic braking connections. For lowering of light loads, a limited amount of power lowering torque is made available in the first master switch position if the operator presses a latch on the master switch handle. Contactor *DB* then opens, contactors *L* and 1*A* close, and the motor is



CONTACTOR CLOSING SEQUENCE

	HOIST					OFF	LOWER				
	5	4	3	2	1		1	2	3	4	5
H	X	X	X	X	X						
L											X
DB							X	X	X	X	
1A	X	X	X	X	X		X	X	X		X
2A	X	X	X	X			X	X			X
3A	X	X	X				X				X
4A	X	X									X
5A	X										X
B	X	X	X	X	X		X	X	X	X	X

NOMENCLATURE OF DEVICES

H	HOIST CONTACTOR
L	LOWER CONTACTOR
DB	DYNAMIC BRAKING CONTACTOR
1A	FIRST ACCELLERATING CONTACTOR
2A	SECOND ACCELLERATING CONTACTOR
3A	THIRD ACCELLERATING CONTACTOR
4A	FOURTH ACCELLERATING CONTACTOR
5A	FIFTH ACCELLERATING CONTACTOR
B	BRAKE CONTACTOR
1OL	AC OVERLOAD RELAY
2OL	DC OVERLOAD RELAY

FIG. 358. Power circuits of crane hoist controller with d-c dynamic braking

connected to the a-c line with approximately twice normal ohms in the secondary circuit.

When the master switch is turned to the fifth position lowering, the motor primary is disconnected from the d-c generator and connected to the line with reversed phase rotation. Accelerating contactors close in sequence. Curve 5–*L* indicates motor performance, and conventional regenerative braking is obtained with overhauling loads. When the load is decelerated from high speed by returning the master switch toward the off position, the accelerating contactors first drop out and then reclose in definite time sequence. If the motor were suddenly thrown from curve 5–*L* to curve 1–*L*, a run-away condition would exist, should the load on the motor be higher than the point of intersection between curve 5–*L* and curve 1–*L*. Definite time relays control the reclosing of accelerating contactors so that curve 1–*L* cannot be reached until after the motor has been decelerated step by step through curves 4–*L*, 3–*L*, and 2–*L* so that a higher braking torque is available on curve 1–*L*.

In designing a d-c dynamic braking controller, care must be exercised in selecting the proper magnitude of d-c excitation current. The d-c current must be high enough to provide sufficiently high maximum torque so that the motor will not run away with the maximum overload the hoist may be called upon to handle. A maximum braking torque of 1.7 times normal motor torque, which corresponds to approximately 2.5 times normal load on the hook, is usually ample to handle normal hook loads with sufficient margin for handling reasonable overloads. On the other hand, the d-c excitation current should be kept low enough to prevent excessive heating of the motor.

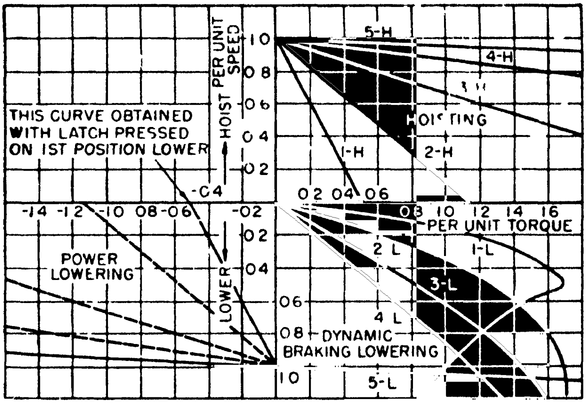


FIG. 359. Speed-torque curves of crane hoist controller with d-c dynamic braking

Floor-Operated Alternating-Current Cranes

Small cranes, involving motor ratings of not more than 35 hp for any motion, may be operated from the floor instead of from cabs. Pendant push or pull button stations or pendant control stations are used, such as described in the preceding chapter. Operating speeds and loads are smaller than on cab-operated general-purposes or bulk-handling cranes. Hoists are generally equipped with either self-locking drives (namely, worm gears) or with mechanical load brakes, both requiring power for lowering. Dynamic braking is not then required, and conventional reversing control is adequate. Mechanical brakes take care of deceleration and stopping.

Motors should preferably be wound rotor type, although squirrel cage induction motors are sometimes used. NEMA has established recommended practices governing the lay-out of floor-operated crane controllers. The coordination between contactor sizes, hp rating, and number of accelerating contactors is given in Table 31. Furthermore,

TABLE 31

CONTACTOR RATING FOR FLOOR-OPERATED A-C CRANES

Standard 8-Hour Rating in Amperes	*Crane Rating Contactors in Motor Primary*		
	Amperes	*Horsepower at 220 Volts*	*Horsepower at 440 and 550 Volts*
25	25	5	7½
50	50	15	25
100	133	35	35

the following stipulations govern design and construction of such controllers:

1. Hoist controllers are of the reversing type, if a mechanical load brake is used. Otherwise, controllers include lowering by electric braking means.
2. Wound rotor motor controllers include plugging protection, using the first accelerating contactor as a plugging step. The minimum number of accelerating contactors is two for motors up to 25 hp and three for motors above 25 hp.
3. Controllers may or may not include motor protection. If protection is included, each motor is equipped with its own set of overload relays, which are selected in accordance with the National Electric Code.
4. Resistors are designed to meet classifications 153, 154, or 155, depending on the magnitude of the starting torque required.

Pilot control stations have contacts for at least the following functions:

Hoist
Lower
Trolley forward
Trolley reverse
Bridge forward
Bridge reverse

If the panel includes protection, the following additional contacts are provided:

Emergency stop
Reset

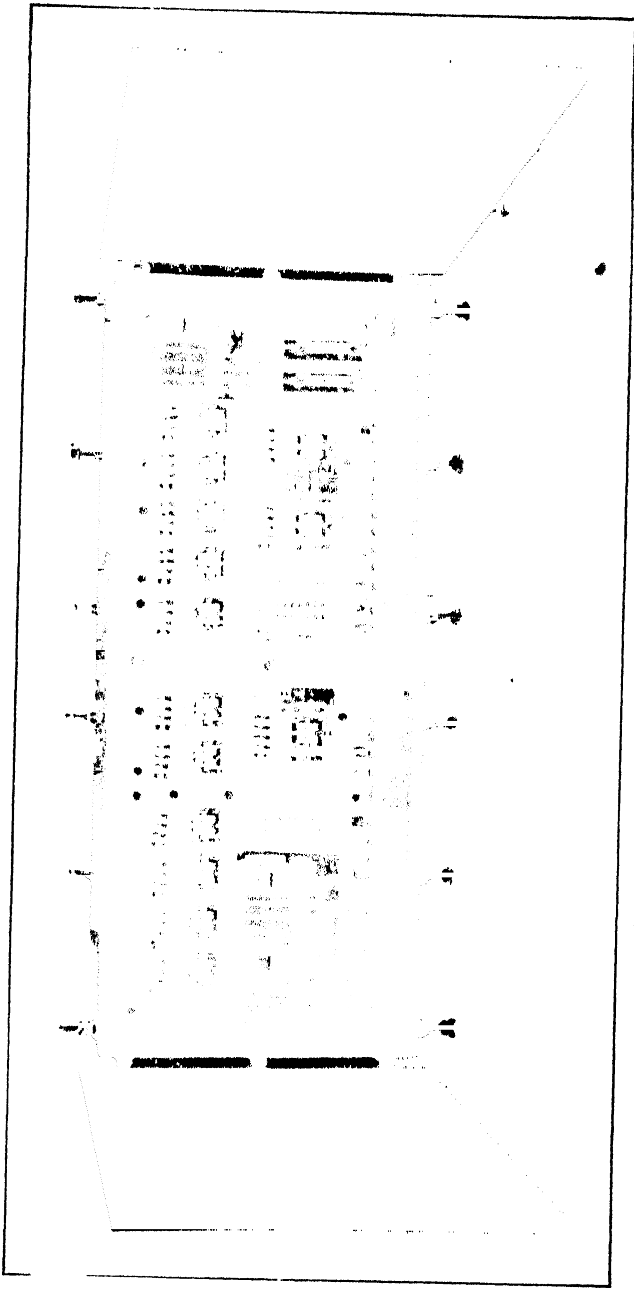


FIG. 360. Enclosed control panel for floor-operated crane.

Provision for additional hand control speed points for either direction of travel may be included as an optional item.

Shown in Fig. 360 is an enclosed a-c control panel for a floor-operated crane. From left to right, it includes control for hoist, trolley, and bridge. Reversing contactors are in the bottom row, accelerating contactors in the top row. Several speed points are provided for each motion, but accelerating relays are omitted. Overload relays are mounted on each unit of reversing contactors. At the extreme right are a main line contactor and a set of control fuses. All outgoing connections are terminated at terminal boards in the front. Resistors are mounted behind the base.

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CHAPTER 20

MAINTENANCE OF CONTROL EQUIPMENT

Controllers, like any other operating equipment, require regular inspection and maintenance. Although magnetic control devices are designed to perform millions of mechanical operations without failure, each device contains parts which are subject to wear, and their replacement at the proper time increases greatly the useful life of the device. Other parts, like contacts, are subjected to arcing which in due course of time consumes the contacts. Maintenance and eventual replacement of contacts prevent device failure. Unusual service conditions such as moist, dusty, or corrosive atmosphere and the like may hasten the wear of devices, unless suitable counter measures are taken.

Manufacturers of control equipment issue detailed instructions on how to service their devices. The control user should observe these instructions carefully. He should also maintain a stock of replacement parts, purchased from the manufacturer of the original equipment, so that worn parts can be exchanged quickly without a prolonged shut-down. Manufacturers are prepared to make recommendations on renewal parts to be kept on hand, and their experience over years of activity in the control field enables them to judge which parts are most likely to fail and what quantities should be stocked for a given installation. The cost of renewal parts should be considered by the plant owner as an insurance premium with which protection is bought against an expensive interruption of plant production.

It is impossible to discuss all maintenance problems in this book because of the great variety of devices available. However, some of the more commonly encountered problems, which are typical for control equipments, are discussed briefly in this chapter.

Inspection Program

Good maintenance depends on regular inspection. Many an expensive shut-down can be avoided if devices are inspected regularly by a skilled electrician and replacements are made before parts fail.

A list should be prepared of items to be checked at each inspection, and this list should be adhered to strictly, to make certain that a complete inspection service is maintained. A regular inspection schedule should be established, as casual inspection at odd intervals is of little value.

A convenient portable instrument should be available for checking voltage, current, and resistance. Combination instruments are on the market, and they are of invaluable assistance in ascertaining unusual operating conditions. The following is a list of points recommended to be checked at regular intervals, preferably once a month:

1. Check control circuit voltage. This check is important, as too high a voltage causes overheating of coils and excessive wear on magnets due to slamming of the magnet armature. Too low a control voltage may cause contactors to close sluggishly so that their contacts freeze.
2. Check for collection of dirt or gum, which may cause excessive mechanical wear or sticking of parts.
3. Check for excessive heating of parts, as evidenced by discoloration of metal parts, charred insulation, or odor. If evidence of overheating is found, ascertain the cause and take corrective measures.
4. Check for loose connections, especially if the equipment is subject to vibration.
5. Check freedom of mechanical movement by operating devices by hand. If sticking or binding is observed, free the parts.
6. Inspect contacts for remaining wear allowance and proper contact pressure. On multi-pole contactors check whether all poles have substantially the same contact pressure.
7. Check condition of flexible shunts and look for any evidence of breaking of strands.
8. Check condition of arc chutes and barriers. A certain amount of burning and scorching is unavoidable, but parts that have been nearly burnt through should be replaced.
9. Look for worn or broken mechanical parts, especially springs, which may require replacement.
10. On oil-immersed devices, check the oil level and look for evidence of sludging. Dirty oil should be replaced by clean oil, after sludge has been removed from device parts.
11. On enclosed panels with gasketed cover, check condition of gaskets and replace if necessary.

12. Look for evidence of water or liquid dropping on the control equipment. It may result in serious damage, and its cause should be remedied.
13. Make a trial operation of the control, checking for proper sequence of contactors and relays, and observe whether any excessive arcing takes place.
14. Operate safety devices, limit switches, overload relays, etc., by hand and check whether they are in operative condition to protect the equipment.

Dust, Dirt, and Grease

Dry dust and dirt may cause excessive wear of mechanical parts, especially pin or knife edge bearings. Dust may include metallic particles, forming a conductive path and causing a short circuit between current-carrying parts of opposite polarity. Dust accumulating on the face of interlock or relay contacts may prevent control current from flowing, even though the contacts are closed mechanically. Dry dust and dirt can be removed effectively by blowing the controller out with an air hose, using a maximum air pressure of 70 pounds per square inch. A heavy accumulation of sticky dust and dirt can be removed with a heavy brush or a wooden scraper.

Grease and oil may cause mechanical sticking of moving parts. They are also conducive to the gathering of dust and thus should be removed. They can be removed by application of a cleaning fluid, such as carbon tetrachloride, with a brush or a rag. Do not soak parts, especially coils, in the cleaner, as it may soften and decompose insulating paints and varnishes. Apply just enough cleaner to loosen the dirt so that it can be wiped off. Small parts are preferably cleaned with a small paint brush, dipped in the cleaner, which permits getting into corners and crevices.

Loose Joints

Control equipment contains many bolted joints. It is important that connections be kept tight, and a periodic inspection should be made to ascertain that panel wiring and outgoing connections are tight. It is especially important on equipments that are subject to vibration.

Connections to resistors are exposed to the alternate heating and cooling of the resistor units, which tend to loosen bolts and nuts holding the connection clamps tight. Resistor boxes are held together by tie rods which are also subjected to alternate heating and cooling. Resistors should be checked at regular intervals, both for tight wire connections and for tight tie rods, as loose joints are likely to cause local heating.

There are bolted current-carrying joints on practically all control devices. Loose joints cause localized overheating, which in turn causes discoloration of parts. If indications are found that a device has been overheated, the high-resistance joint can be located by a millivoltmeter. The overheating leads to the formation of oxide films on the parts joined together. To reduce the resistance of the joint, clean the surfaces with a fine file and bolt them together again. Do not use sandpaper or silicon carbide paper.

Corrosive atmospheres may attack the metal in bolted joints and high-resistance films may form. If they do form, they should be filed off, in the same way as oxide films. Corrosion-resisting plating may prove helpful.

Joints which carry high current, as in bus bars, can be successfully protected by silver plating. When silver oxidizes, the resistance of the oxide film is higher than the resistance of the pure metal. However, when the joint heats, the silver oxide is reduced again to pure metal and thus silver-covered joints are self-protecting.

When gases containing sulphur are present in the atmosphere conducting parts are corroded quite rapidly and high-resistance films form. If such a condition exists, the controller should be enclosed in a tightly gasketed enclosing case, or an oil-immersed controller should be installed.

Care of Contactors

Troubles on contactors may be mechanical or electrical. Contactors have mechanical parts which move and are subject to wear. On contactors which operate frequently, the proper mechanical alignment of parts should be checked periodically, following instructions issued by the control manufacturer. It is important that contactor armatures move freely and with a minimum of mechanical friction; otherwise, the magnet may be unable to develop sufficient pull to close the contactor and drop-out may likewise be impeded. If parts bind, they should be readjusted or, if they are worn to such an extent that adjustments cannot be maintained, new parts should be used.

Shunts are subjected to frequent flexing. Although properly designed shunts are able to stand this flexing for millions of operations, the attack of corrosive atmosphere may destroy the fine strands of wire and cause shunts to break prematurely. Shown in Fig. 361 is a shunt which was destroyed by the presence of hydrogen sulphide in the air. The strands were weakened so that they broke when the shunt was flexed. When assembling shunts during maintenance work, care should be taken to install them in exactly the same manner in which they were originally assembled by the manufacturer.

Pole faces of a-c magnets cannot be protected against rusting by protective painting or plating, since a tight seal between magnet surfaces is necessary to prevent noise or chattering. Application of a thin film of oil helps to prevent the formation of rust, but it must be realized that such an oil film is conducive to the accumulation of dirt. The dirt, in turn, may cause contactors to stick closed. Oil may also dissolve the varnish between laminations, forming a gum.

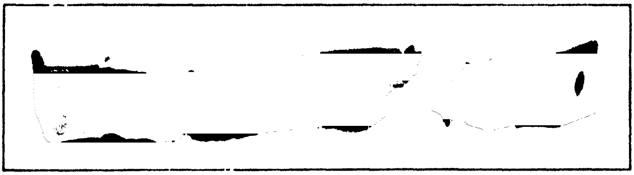

FIG. 361. Contactor shunt corroded by hydrogen sulphide.

In time, oil oxidizes to form a sticky residue. Cleaning the pole faces periodically prevents gum from collecting.

Noisy magnets of a-c contactors are due to two common causes, broken pole shader or low control voltage. Broken pole shaders result in flux pulsations at twice control voltage frequency, causing a loud hum or even chattering. Broken pole shaders should be replaced immediately, as the chattering results in excessive pounding of the laminated magnets. Misalignment of contactor parts may have the same effect.

Low control voltage may have the same effect. Even with pole shaders the magnet flux is not absolutely uniform but contains peaks and valleys, alternating at twice control voltage frequency. If the control voltage is too low, the flux at the low point may be insufficient to hold the magnet sealed against the contact spring pressure, resulting in loud humming or chattering. Control voltage should be checked at the coil terminals, as a high-resistance contact in the pilot circuit may result in low voltage at the coil, even though the terminal voltage of the control circuit may be up to normal.

High control voltage is equally objectionable. It may result in overheating of the coils and in excessive wear of magnet pole faces and other moving parts owing to excessive mechanical force being applied by the magnet. If the control voltage is higher than normal plus the customary 10 per cent allowance, either the control voltage must be reduced or special coils must be used.

Laminated magnets of a-c contactors are subjected to greater wear than the solid magnets of d-c contactors. On contactors operated frequently the ends of the laminations may become mushroomed, destroying the insulation between the laminations and resulting in eddy currents, increasing the heating of the laminations and the coil. If mushrooming occurs, laminated magnets have to be replaced. They may wear out faster than other structural parts of contactors.

Care of Coils

There are three common causes of coil failure:

1. Breakage of coil wire.
2. Overheating.
3. Corrosion.

The first cause is the least likely to occur. Although many coils are wound of very fine wire, the use of a good grade of wire and proper control of manufacturing methods have practically eliminated internal coil failures due to wire breakage. However, the weakest point in any shunt coil is the connection of the terminal or lead wire to the coil wire. This connection may break if the coil is subjected to excessive vibration.

Improper handling or storing of spare coils may cause this joint to break. Although lead wires are strong enough to support the weight of the coil, they should never be used as carrying handles. When storing coils with terminals, care must be taken not to bend or otherwise damage the terminals.

Overheating is a common cause of coil trouble. The fine wire of shunt coils melts and open-circuits the coil if the temperature inside the coil becomes excessive. Overheating may be caused by high control voltage. On a-c contactors an excessive current will flow through the coil if the contactor fails to seal properly on account of mechanical binding.

Corrosion may occur in d-c coils if they absorb moisture from the air. Electrolytic action may set in between points of different potential, destroying the coil wire quickly and causing an open circuit. It is therefore important to store coils in a dry place and to keep the air reasonably dry at the location where controllers are installed. For use in locations with high humidity, such as in the tropics, coils should be used which have been given a special moisture-resisting finish.

Coils that have become wet should be thoroughly baked in an oven at a temperature between 110 and 125 C. Coils should also be baked if they have been dipped in carbon tetrachloride to remove oil or grease. If it is necessary to apply a moisture-resistant finish, use an approved insulating paint or varnish that has been approved by the coil manufacturer. Apply the paint while the coil is still warm from baking. A proper type of paint must be used, since some paints and varnishes contain thinners that attack coil and wire insulation.

Copper Contact Tips

Contacts are naturally subject to a considerable amount of wear. The interruption of current causes arcing, which burns off contact material and roughens the contact surfaces. Any contact requires attention and occasional replacement. Spare contacts should be kept on hand, especially when contactors operate frequently.

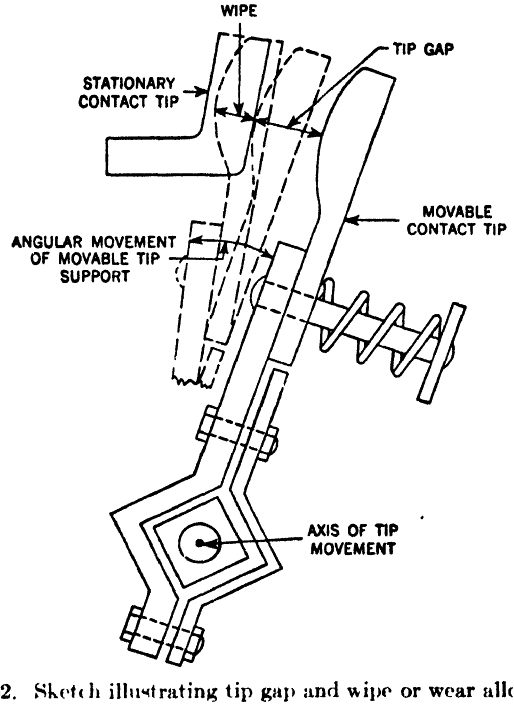

FIG. 362. Sketch illustrating tip gap and wipe or wear allowance.

It is an essential requirement for good contact performance that contacts be adjusted properly. When they close, the movable contact should wipe in with a rolling and sliding motion. This motion breaks oxide films which may form on the contact surfaces and serves to keep the contact resistance low. Proper spring pressure is required to enable the contacts to carry their rated current. As the contacts wear away, the spring pressure is naturally reduced, and the contactor design makes provision for a certain wear allowance which should not be exceeded.

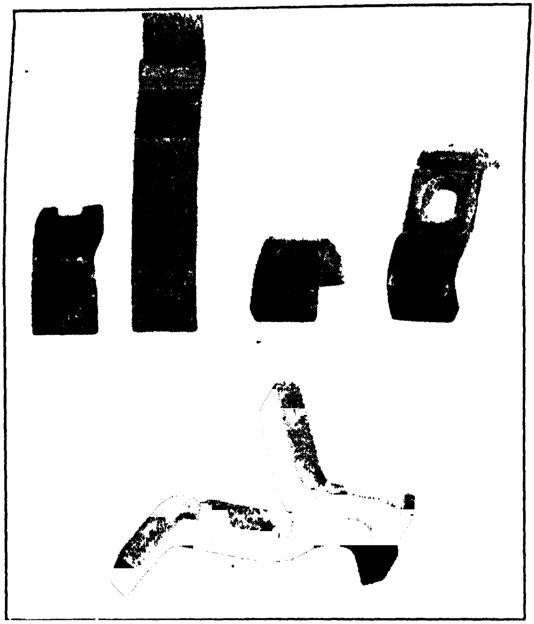

FIG. 363. Contact tips showing normal wear, not requiring replacement.

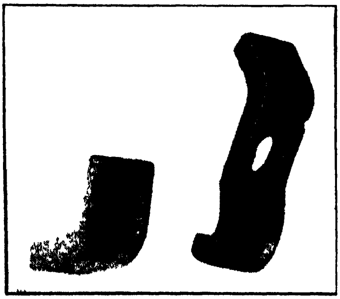

FIG. 364. Worn contact tips requiring replacement.

Figure 362 illustrates the significance of tip gap and wear allowance. The instruction sheet supplied by the manufacturer for a certain contactor states the tip gap for new contact tips and the wear allowance, usually measured between two points of the contactor which are readily accessible, for instance at the tip support. When the specified wear allowance has been used up, the contact tips should be replaced.

Contact tips will naturally become roughened in service. They cannot be expected to remain smooth and clean. If contact tips look like Fig. 363, they just show normal wear and should be left alone. When the tips close, they should have good alignment and make good contact. Contact tips should never be lubricated with oil or grease, because the burning of the oil upon current interruption increases the heating of the contacts, increases the contact resistance, and shortens their life.

If evidence is discovered that contacts overheat, which shows up by discoloration, it is an indication that copper oxide has formed. Copper oxidizes slowly at room temperature but rapidly at elevated temperatures. Copper oxide has a much higher resistance than pure copper and the formation of an oxide film leads to overheating. If the natural sliding motion of the contacts does not break the oxide film, the contacts should be cleaned by a few strokes with a fine file. Do not file too often, as this removes material unnecessarily and reduces the tip life. Never use sandpaper or silicon carbide paper.

When contact tips have worn to such an extent that the adjustments, as specified in the manufacturer's instructions, can no longer be maintained, new tips should be installed. The contact tips as shown in Fig. 364 have worn to such an extent that proper alignment is no longer obtained, and they should be replaced.

What may happen if contact tips are permitted to stay in service too long is illustrated by Fig. 365. The tips of this contactor had worn away so that contact alignment and contact pressure were no longer maintained. The result was severe overheating, causing the contact tips to melt and arc violently, with resultant damage to other contactor parts. It could have been avoided by replacing contact tips at the proper time.

Welding or freezing of contact tips may be caused by excessive heating. Contacts which stay closed for long periods of time without opening do not have a chance to clean their contact surfaces as often as contactors which operate more frequently. Contacts which overheat and freeze while staying closed should be replaced by tips made of other materials. Silver tips are more suitable for applications where contactors stay closed for long time intervals, and replacing copper tips by silver tips may eliminate freezing trouble under such service conditions.

Many control applications require that contactors close on inrush currents considerably in excess of the steady state currents they have to carry. Freezing of contact tips often occurs when the contact tips just touch and pass the inrush current. It can be traced in most cases to improper build-up of contact pressure which causes the contacts to weld together before the rolling and sliding motion to the final closed position has been completed. The most common causes of contactor freezing upon closing are:

1. Low control voltage, either at the control source or at the contactor coil on account of excessive resistance in the pilot circuit. It makes the armature of the magnet sluggish in closing, and the armature hesitates in its travel at the instant the contact tips touch. This condition can be remedied by raising the control voltage (if possible), by using lower voltage coils, or by eliminating the cause of high resistance in the pilot circuit.

FIG. 365. Contactor damaged by leaving contact tips in service too long.

2. Poor mechanical adjustment may have the same effect, as excessive friction of the moving parts also may cause the magnet to close sluggishly. The contactor should be given proper mechanical alignment, and worn parts should be replaced if necessary.
3. Contacts may bounce open, after they have first closed, and then reclose, causing an arc to be drawn, which may soften the

tip material sufficiently to make the tips weld together. Contact bouncing is an inherent fault of a given contactor design, and the manufacturer should supply redesigned parts which eliminate the bouncing.

If severe service conditions or the presence of corrosive atmosphere make it impossible to prevent freezing in spite of careful maintenance, special contact tips of weld-resistant material may be used in place of standard tips. Various alloys and sintered materials are available which are superior to either copper or silver in their non-welding qualities. Metals which have a high degree of weld resistance may have other undesirable characteristics, such as high contact resistance, short life because of excessive burning, or low interrupting ability. Therefore, the control manufacturer should be consulted for his recommendations, which will be governed both by the design characteristics of the contactor and by the specific requirements of the application.

Silver Contact Tips

Many standard small contactors, NEMA size 1 and smaller, are equipped with fine-silver contact tips. Silver oxidizes more slowly than copper, and silver oxide has a lower resistance than copper oxide. As the film of silver oxide forms, the contacts are heated and the silver oxide is reduced to metallic silver. Thus silver contacts are self-cleaning, and it is not necessary to remove the oxide film.

The presence of sulphur in the atmosphere is very detrimental to silver contacts. Silver sulphide is formed readily. The sulphide film has a high resistance. If tip pressure is light and the circuit voltage is low, current may be prevented entirely from flowing. Silver sulphide is darker in color than silver oxide. If it forms, the contacts must be cleaned by filing.

Silver contacts are also used on larger contactors on applications where contactors stay closed for long periods of time, as oxidation is not likely to cause trouble as in the case of copper contacts. However, silver is softer than copper and has lower resistance to mechanical wear. It also wears away more rapidly than copper under the effect of arcing. Silver contacts should not be used on large contactors that operate frequently.

Another shortcoming of silver is its greater weldability. On contactors which close on high inrush currents, silver contacts are likely to weld more readily than copper contacts, and silver tips should be used with caution. They may operate satisfactorily for a certain number of operations, and then they weld at increasingly frequent intervals. *If contact tips start to weld after a period of proper operation, they should be replaced by new tips.*

If silver contacts give trouble on an application for which copper contacts are not suited, consult the manufacturer and obtain his recommendations on special alloyed or sintered tips.

Service from Manufacturer

If chronic trouble develops which cannot be remedied by the user, he should contact the manufacturer of the control equipment, send him a sample of the damaged or broken part, and give as much of the following information as possible:

1. Complete nameplate data of the controller.
2. Nameplate data and function of the equipment on which the controller is used.
3. Manufacturer's requisition or order number, if available.
4. Duty cycle and details of operation.
5. Length of time that the equipment has been in service and estimated number of operations.
6. Voltage and frequency conditions at the controller and other pertinent electrical data.
7. Detailed description of the circumstances under which the failure occurred.
8. Information on any unusual service conditions.

The following is a list of unusual conditions, which should be called to the manufacturer's attention, as special construction or protection of the control apparatus may be required:

Exposure to damaging fumes.
Operation in damp places.
Exposure to excessive dust.
Exposure to gritty or abrasive dust.
Exposure to steam.
Exposure to excessive oil vapor.
Exposure to salt air.
Exposure to vibration, shock, and tilting.
Exposure to explosive dust or gases.
Exposure to the weather or to dripping water.
Operation in ambient temperatures above 40 C.
Installation at altitudes above 6000 feet.

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INDEX

A-c contactors, 170
A-c control circuits (basic), 355
  acceleration, 362
  dynamic braking, 373
  jogging, 356
  plugging, 368
  pole changing, 360
  reduced voltage starting, 358
  reversing, 356
  starting, 356
A-c motor characteristics, 87
  pole-changing motors, 93
  squirrel cage motors, 91
  synchronous motors, 128
  wound rotor motors, 108
Accelerating contactors, 163
Acceleration, of a-c motors, 362
  of d-c motors, armature control, 332
    field control, 344
Adjustable-voltage systems, 66
  acceleration, 72
  deceleration, 72
  series exciter, 74
  shunt generator control, 67
  three-field generator control, 75
American Standard symbols, 5
Amortisseur winding, 132
Amplidyne, characteristics of, 82
Amplidyne control circuits, 377
  alternator voltage, 395
  current control, 385
  current limit control, 386
  d-c generator voltage, 382
  positioning control, 392
  reversing plugging, 388
  speed control, 391
  stabilizing, 378
Angle switching of synchronous motors, 140
Anti-hunting, 378
Armature control, 58
Armature shunting, control circuits, 346
  crane control, 506
  series motor performance, 35
  shunt motor performance, 61
Auto-transformer starting, basic circuits, 358
  magnetic compensator, 465
  manual compensator, 449
  motor performance, 96

Base material, 283
Bimetal relays, 404
Brakes, band type, 426
  connections of, 435
  disk type, 426
  duty cycle application, 434
  operators, 428
  shoe type, 427
  stopping of load, 432
  torque rating of, 430
  types of, 425
Bureau of Mines, 310
Bus bars, 289

Cable, use on panels, 290
Calculation of performance curves, 28
Cam switches, 447
Capacitor discharge, 164
Centrifugal switches, 231
Circuit breakers, 147
Closed cycle control, 78
Coil inductance, 156
Commutation limit, 24
Compensator (starting), magnetic, 465
  manual, 449
Compound motors, 64
Connection diagrams, 15
Construction diagrams, 18
Contact tips, copper, 577
  silver, 581

Contactors, a-c types, 170
    d-c operated, 176
    high-voltage, 182
    low-voltage, 173
    rating of, 178
    secondary, 181
  d-c types, 145
    accelerating, 163
    pneumatic, 168
    rating of, 153
    shunt type, 147
Control centers, 312
Control desks, 316
Control power sources, 355
Control transformers, 203
Counter emf acceleration, 338
Crane controllers, a-c operated, 537
    cab-operated, 537
    d-c dynamic braking, 565
    duplex control, 545
    floor operated, 567
    graduated plugging, 548
    hoist control, general, 546
    protective panels, 538
    reversing control, 541
    single-phase lowering, 555
    Thrustor load brake, 551
    unbalanced stator voltage, 559
  d-c operated, 489
    armature shunting, 506
    bridge control, 494
    cab-operated, 489
    construction of panels, 530
    duplex bridge control, 499
    dynamic braking control, 508
    floor-operated, 531
    grab bucket hoists, 522
    hoist control, 511
    installation of panels, 530
    protective panels, 491
    series-parallel control, 502
    trolley control, 494
Current control, 385
Current limit acceleration, a-c control, 363
  d-c control, 337
Current limit control, 386
Cutler-Hammer, Inc., a-c crane control, 559
  speed governor, 231
Cutler-Hammer, Inc., synchronous motor control, 478
Cycling, 325

Damping motor, 72
D-c contactors, 145
D-c control circuits (basic), 322
  acceleration, control of, 337
  armature acceleration, 332
  armature shunting, 346
  cycling, 325
  dynamic braking, 348
  field acceleration, 344
  jogging, 324
  plugging, 350
  reversing, 327
  shunt field, control of, 330
  starting, 322
D-c motor characteristics, 20
  compound, 64
  general, 22
  series, 25
  shunt, 50
Definite time acceleration, a-c control, 367
  d-c control, 340
Desks, 316
Device markings, 10
  table of, 12
Diagrams, connection, 15
  construction, 18
  elementary, 14
  wiring, 13
Doubly fed induction motor, 128
Draw-out controllers, 313
Drum switches, 443
Dynamic braking, adjustable-voltage system, 70
  control circuits, 348
  crane hoists, d-c control, 511
  d-c of a-c motors, control circuits, 373
    crane hoist control, 565
    squirrel cage motor performance, 102
    wound rotor motor performance, 115
  series motor performance, 39
  shunt motor performance, 62

Dynamic braking, wound rotor motor performance, 112

Ebony asbestos, 285
Electric Controller and Manufacturing Co., a-c crane control, 555
  Youngstown limit switch, 238
Electronic relays, 240
Electronic timers, 243
Elementary diagram, 14
Enclosing cases, Bureau of Mines, 310
  classification of, 294
  clearances for, 303
  design of, 302
  hazardous locations, 305
  materials for, 304

Face plate controllers, 410
Field circuit, control of, 330
Field control, shunt motors, 63
  synchronous motors, 136
Field switching, 55
Field weakening, 62
Float switches, 227
Frameworks, 293
Frequency changer sets, 126
Frequency control of secondary contactors, 365
Frequency converters, 98
Fuses, current-limiting, 416
  low-voltage, 413

General-purpose controllers, 451
  a-c motor controllers, 459
    combination starters, 462
    full-voltage starters, 459
    reduced-voltage starters, 463
    synchronous motor controllers, 470
    wound rotor motor starters, 466
  d-c motor controllers, 451
    definite time starters, 455
    mechanical time starters, 454
    reversing starters, 456
Grab bucket hoist control, 522
Graduated plugging control, 548

Hazardous locations, 305
Holding coils, 328

Induction motors, 87 ,
Inductive circuits, switching of, 55
Interlocks, 154

Jogging, 324

Knife switches, 196
Kraemer sets, 123

Limit switches, geared type, 235
  power type, 238
  track type, 233
  Youngstown, 238
Loss of field protection, 399

Magnetic control, advantages of, 145
Magnetic time delay relays, 161
Magnets, a-c 170
Maintenance, care of coils, 576
  care of contactors, 574
  copper contact tips, 577
  dust, dirt, grease, 573
  inspection program, 571
  loose joints, 573
  silver contact tips, 581
Manual controllers, 440
Master switches, 221
Maximum torque, 24

Neutralizing, 69

Operators, protection of, 397
Operators' panels, 316
Overload protection, 400
Overload relays, compensated, 407
  general, 401
  instantaneous, 408
  inverse time, 410
  thermal, 402

Packaged control units, 320
Panel construction, 283
Panels, open, 291
Parallel operation, series motors, 27
  shunt motors, 54
Part winding starting, 134
Performance curves, calculation of, 28
Phase reversal protection, 298
Photoelectric relays, 245
Phototubes, 246 ✓

Pilot devices, 216
Pliotron oscillator, 252
Plugging, control circuits, 350
  d-c motor performance, 34
  squirrel cage motor performance, 101
  synchronous motor performance, 136
  wound rotor motor performance, 112
Pneumatic contactors, 168
Pole-changing control, 360
Pole-changing motors, 93
Potential interlocking, 357
Power factor correction, 142
Power selsyns, 118
Pressure switches, 225
Protection, 397
  loss of field, 399
  overload, 400
  phase reversal, 398
  short-circuit, 412
  undervoltage, 398
Push buttons, 216

Rectifiers, 205
  copper oxide, 206
  selenium, 207
Reduced voltage starting, control circuits, 358
  motor performance, 95
Regenerative braking, squirrel cage motors, 101
  wound rotor motors, 112
Regulating exciters, 81
Regulator, voltage, 212
Regulex, 81
Relays, a-c control, 187
  current limit, 189
  d-c control, 155
  electronic, 240
  magnetic time delay, 161
  motor timing, 188
  overload, 401
  phase failure, 190
  phase reversal, 190
  photoelectric, 245
  resonant, 193
  thermal, 403
  voltage, 166
Resistance, internal, of series motors, 31
  of shunt motors, 59
  of wound rotor motors, 110
Resistors, 256
  application data, 259
  cast grid, 261
  classification, 257
  duty cycle rating, 272
  effect of altitude, 269
  enameled, 274
  enclosed, 270
  punched grid, 263
  ribbon wound, 265
  spacing, 268
  Thyrite, 280
  wire wound, 267
Rheostats, 274
  liquid type, 279
Reversing, a-c control circuits, 356
  d-c control circuits, 327
  induction motors, 100
  series motors, 28
  shunt motors, 54
Rototrol, 81

Scherbius sets, 124
Secondary frequency control, 365
Secondary resistance, 109
Series exciter, 74
Series generator connection, 37
Series motors, 25
Series-parallel control, 502
Short-circuit protection, 412
Shunt contactors, 147
Shunt generator connection, 38
Shunt motors, 50
Shunted armature connection, ser motors, 35
  shunt motors, 61
Shunted motor connection, 34
Single-phasing, 105
Slate, 285
Slip, 89
Slip cycle impedance relay, 481
Slip frequency relay, 474
Slip regulator, 279
Solenoids, 419
Spacing, minimum, 347

Speed control, series motors, 32
  shunt motors, 58
  wound rotor motors, 109
Speed governor, 231
Speed-regulating sets, 121
Speed-torque curves, 20
Squirrel cage motors, 91
Stability limit, 47
Stabilizing, 378
Starters, a-c types, auto-transformer, 465
    combination, 462
    full-voltage, 459
    primary reactor, 464
    reduced-voltage, 463
    wound rotor, 466
  d-c types, definite time, 455
    mechanical time, 454
    reversing, 456
Steel mill auxiliaries, 489
Steel panels, 284
Stopping of load, 132
Suiciding, 69
Switches, cam, 447
  centrifugal, 231
  drum, 443
  float, 227
  knife, 196
  limit, 233
  master, 221
    rotation of, 490
  motor-starting, 447
  plugging, 232
  pressure, 225
Symbols, 5
Synchronizing phenomena, 136
Synchronous motor controllers, 470
  field application by current-time relay, 478
    by slip cycle impedance relay, 481
    by slip frequency relay, 474
    by timing relay, 472
  field removal, 476
Synchronous motor controllers, squirrel cage protection, 477
Synchronous motors, 129
Synchronous speed, of flux, 89
  of motor, 130

Terminal markings, 10
Terminals, 291
Thermal relays, 403
Thermostats, 228
Three-field generator, 75
Thrustor, 423
Thrustor load brake, 551
Thyrite, 280
Timer, electronic, 243
Transformers, constant-voltage, 204
  control, 203

Unbalance of stator voltage, crane control, 559
  squirrel cage motor performance, 103
  wound rotor motor performance, 116
Unbalanced secondary resistor, 114
Undervoltage protection, 323
Undervoltage release, 322

V-curves of synchronous motor, 142
Voltage regulator, 212
Voltage stabilizer, 204

Westinghouse Electric Corp., a-c crane control, 562
  inverse-time relay, 410
  Rototrol, 81
Wilson-Ritchie system, 511
Wiring of panels, 286
Wiring diagrams, 13
Wound rotor motors, 108
Wye-delta starting, 97

Youngstown limit switch, 238